

INTRODUCTORY ECONOMIC GEOLOGY

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TO MY WIFE
Coralynn G. Tarr

PREFACE

This is an introductory textbook. The objective is to present, in a manner as simple as possible, a general picture of the earth materials used by man. The book is the outgrowth of many years of teaching the subject to students, who, for the most part, have had only an introductory course in geology. Such students are acquainted only with the common minerals and rocks and know little about their origin. Only the most common ore minerals are considered in this text and, although some knowledge of geology is presupposed, much of the material could be understood by the layman.

After some brief historical notes on man's use of earth materials, the successive steps in the formation of all types of mineral deposits are developed. The subsequent treatment is by materials or groups of materials. The details regarding mineralogy, mode of occurrence, and other phases of the subject have been reduced to a minimum, as the average individual will not remember them and must look them up if he is in need of them. The uses of the various earth materials have been given rather fully, as this phase is interesting to all. The methods of mining and treatment of most of the materials are given, as the author has found that students are consistently interested in this phase of the subject. The author's interpretation of the origin of most materials is given, as the selected readings at the end of each subject treated enable anyone interested to go further into the subject.

The author has made much use of the large volume of literature dealing with earth materials. These sources are indicated in the choice of the selected readings and the excellent bibliographies which they contain. Acknowledgments for illustrative material accompany the illustrations. Special acknowledgment is made of the courtesy of the director of the U. S. Bureau of Mines in providing the author with the latest statistics of mineral production. The publications of the U. S. Bureau of Mines and of the U. S. Geological Survey have been an invaluable source of material. Special acknowledgment is due, also, to L. M. Neumann of Tulsa, Oklahoma, for reading and criticizing the chapter on petroleum.

And, lastly, the author acknowledges his indebtedness to his wife, Coralynn G. Tarr, without whose indefatigable aid at every stage of the work, he could not have prepared this volume.

W. A. TARR.

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CONTENTS

	PAGE
PREFACE.	vii

PART I

HISTORY AND ORIGIN OF EARTH MATERIALS

CHAPTER	
I. INTRODUCTION	3
II. EARTH MATERIALS USED BY ANCIENT MAN AND THEIR SIGNIFICANCE IN MODERN LIFE	6
III. GENERAL PRINCIPLES OF THE FORMATION OF MINERAL DEPOSITS. . . .	15

PART II

METALLIC EARTH MATERIALS

IV. IRON.	85
V. FERRO-ALLOY METALS.	116
VI. COPPER	145
VII. LEAD AND ZINC.	194
VIII. GOLD AND SILVER.	235
IX. TIN	289
X. ALUMINUM.	297
XI. MINOR METALS.	306

PART III

NON-METALLIC EARTH MATERIALS

XII. COAL	339
XIII. PETROLEUM AND NATURAL GAS	383
XIV. STRUCTURAL MATERIALS.	465
XV. MATERIALS USED CHEMICALLY.	536
XVI. MATERIALS OF MISCELLANEOUS USES.	594
INDEX.	635

PART I
HISTORY AND ORIGIN OF EARTH MATERIALS

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INTRODUCTORY ECONOMIC GEOLOGY

CHAPTER I

INTRODUCTION

The study of the earth materials which man has adapted to his use is called *economic geology* or *applied mineralogy*. If the inclination of the student leads him to inquire how these materials were obtained from the earth, he will take up *mining geology*, and if he desires information as to how they, especially the metals, were removed from the substances in which they are found in the rocks, he will study *metallurgy*. The last two subjects are not discussed (except in the briefest manner) in this book, which deals with the *distribution, mode of occurrence, uses, and origin* of the common mineral substances.

Economic geology furnishes information about the geographical distribution of the different earth materials. No one area of the earth has a monopoly of a specific substance, especially of the more common ones. In a country as large as the United States, this is very fortunate; as, for example, if it were necessary for California to obtain all the cement she uses from the greatest cement-producing area in the United States, the Lehigh Valley in Pennsylvania, the long haul would seriously increase its cost for her. But California has in abundance the materials necessary for the manufacture of cement (she was the second state in its production in 1928); hence, a long haul is unnecessary. It must not be thought, however, that the distribution of natural resources is ideal, for it is not, many areas being without the majority of such materials. The location of states and cities came about with no thought of a future need for these natural resources. Some localities are fortunately situated and others are not. The building materials used in a given place usually reflect the resources of the area. Such an adaptation to local resources is especially noticeable in Europe. The general geographical distribution of different economic products is shown by the maps in this book.

The manner in which these materials are found in or on the earth (generally spoken of as the *mode of occurrence*) should be a matter of general interest. Economic geology furnishes information on this subject and, also, on the matter which is, after all, of the most vital interest, *i.e.*, the *origin* of these various materials

The study of mineral deposits has progressed with tremendous strides in the last 50 years, and yet there is a vast amount of work still to be accomplished. The great body of facts now available gives, however, a reasonably clear picture of how the great deposits of minerals were formed.

The mineral substances used by man readily fall into two large divisions: *metallic substances*, such as gold, iron, lead, and copper; and *non-metallic or earthy substances*, such as coal, building stone, clay, and salin. In 1928, the total value of the non-metallic products in the United States exceeded that of the metallic by \$2,827,000,000. The total value of our mineral products for that year was \$5,400,000,000 (Fig. 1). Figure 1 is a graph showing the value of the total mineral production in the United States from 1880 to 1928.

Within each of the major divisions, materials used for a similar purpose have been grouped together in this book whenever possible, as for example, under Structural Materials: stone, clay, cement, sand, gravel, lime, and gypsum. A number of miscellaneous substances had to be taken up separately, and these are placed in one chapter.

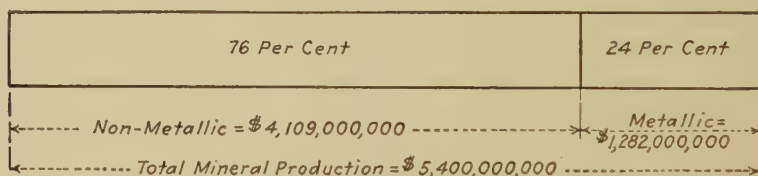


FIG. 1.—Comparative values of metallic and non-metallic productions and total mineral production of the United States in 1928. (Data from U. S. Bur. Mines.)

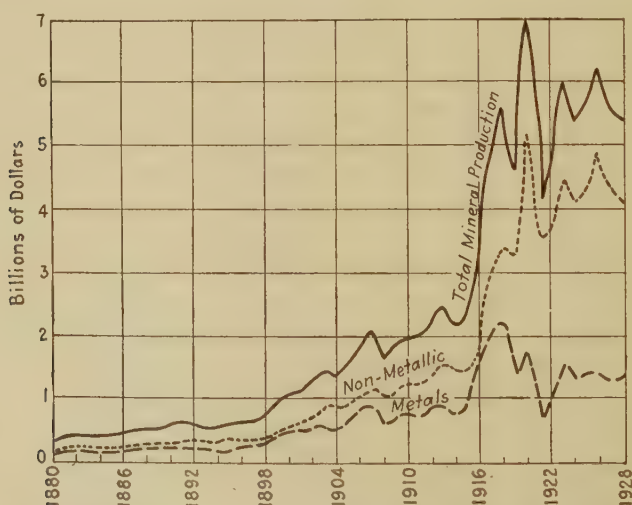


FIG. 2.—Value of total mineral production in the United States from 1880 to 1928. (Data from U. S. Bur. Mines.)

Graphs are used to show production over periods of time, rather than production figures, as the former indicate at a glance the growth or fluctuations in production. Charts are made use of, also, to show the rank of different states and regions in the production of the United States, and of the country, as a whole, in world production.

CHAPTER II

EARTH MATERIALS USED BY ANCIENT MAN AND THEIR SIGNIFICANCE IN MODERN LIFE

Food is required by all animals, and a shelter of some kind has been adopted by many when their physical environment rendered it necessary. Man differs nowise from all other living creatures in these respects, but he does differ in that he alone has successfully adapted to his needs the minerals and rocks that form the solid earth. His use of them dates far back in his history, probably to the first time when all his efforts were not required to secure food.

The names *eolithic* (Gr. *eos* = dawn + *lithos* = rock), *paleolithic* (Gr. *palaios* = old + *lithos*), and *neolithic* (Gr. *neos* = new + *lithos*) are applied to the earliest cultural periods through which primitive man passed. These are known collectively as the *stone ages*. Later, as man acquired greater knowledge of earth materials and skill in utilizing them, further cultural stages, the *copper age*, *bronze age*, and *iron age* (which includes the present), were added to his history.

THE STONE AGES

The degree of craftsmanship displayed by primitive man determines his position in the divisions of the stone age—his advancement in the scale of civilization. As he progressed, he became wonderfully proficient in making different stone implements and other articles—a proficiency at which we should marvel when we remember that he had no tools other than those made of the same material upon which he was working. The men of the stone ages were true artisans.

Chert (white) and *flint* (black) were the first earth materials utilized by primitive man. This was doubtless due to the fact that these materials break naturally into chips and flakes with sharp cutting edges. The discovery of these edges may have been the accident of stepping upon a sharp flake, or it may have been the result of a direct mental process—which, we shall never know.

The first implements and utensils produced by ancient man (*eolithic*) were very crude, but throughout the *paleolithic* period craftsmanship steadily improved. It reached a climax in the *neolithic* age, when men were capable not only of producing weapons, implements, and utensils in an infinite variety of shapes but also undertook the extra task of polish-

ing them. Besides chert and flint, they likewise used *quartz* and *quartzite*. Before the close of the stone ages, a considerable artistic skill had been developed in carving figures from *soapstone* and in engraving on *slate* and *limestone*. Some of these artistic objects were polished. The paleolithic and neolithic periods could be subdivided on a basis of the workmanship shown by these various products.

Clay seems to have been the next material, after chert and flint, used extensively by primitive man. Until recent times, ancient clay products had been found only in remains of the neolithic age, but late discoveries in Egypt by Sir Flinders Petrie prove that the men of the Solutrean period (late paleolithic) made pottery comparable in quality to that of the later ages. This has been called the "Badarian culture" and is dated 13000 to 12000 B.C. (the date of the neolithic is about 10000 to 7000 B.C.). Pottery of an earlier date than the neolithic had not been found in Europe until 1925, when the discovery was made in southern Moravia of burned clay figures among the implements of Aurignacian (middle paleolithic) men. If this discovery is authentic, clay working dates back farther in Europe than it does in Egypt, for a date commonly assigned to the Aurignacian is 30000 to 20000 B.C.

The use of clay must have been widespread during neolithic times, for we find that numerous races were very proficient in the manufacture of clay products as far back as 6000 to 5000 B.C. The Chaldeans were making brick and tile in 5700 B.C., and numerous other Asiatic nations were using clay products in the periods following that date. Terra cotta figures were made in Egypt as early as 2300 to 2000 B.C., and pottery and other clay products had been made there for 10,000 years.

In working out the history of man, these ancient clay products have been of inestimable value. It is fortunate for us that the Chaldeans, Babylonians, and other ancient peoples did not have printing paper but had to use clay tablets for transmitting messages and making records; because, due to the permanency of clay, a wonderful record of those races is left to us.

From these early beginnings, clay working comes on down through the ages, always showing improvement and an increase in the variety of products. At present, the United States produces annually over \$400,000,000 worth of clay products, and if the value of the clay used in manufacturing cement is included, another \$100,000,000 must be added to this amount.

Primitive men used other materials besides the important flint, chert, and clay. The drawings they have left upon the walls of caverns are sometimes in colors. They had learned to use *ochers* (mixtures of iron or manganese oxides and clay) producing red, yellow, and brown colors. Another piece of craftsmanship was their perforation of shells and teeth for necklaces and of bone for needles and other articles.

Primitive man was probably as favorably attracted by minerals that possessed marked color and brilliancy as is modern man, for he early learned to shape and drill them for ornaments. *Carnelian* (a red variety of quartz) beads, shaped and smoothed and drilled with large holes, but not polished, were found among Badarian objects and date to 13000 or 12000 B.C. Undrilled beads of carnelian, *rock crystal*, and *smoky quartz* have also been found among remains of that period. During the old kingdom of Egypt (4000 B.C. or earlier), carved beads of carnelian, drilled and having a fair polish, were made.

About this time, the Egyptians were carving all sorts of figures from *granite*, *basalt*, *porphyry*, *alabaster*, *sandstone*, and *limestone*; but, although they smoothed them slightly, they did not really polish their figures until about 1500 B.C. They used sand or fine-grained rocks to do this. During the Eleventh and Twelfth dynasties, they were using carnelian, *chalcidony*, *amethyst*, *rock crystal*, *smoky quartz*, *calcite*, *turquoise*, *lapis lazuli*, and *soapstone*. At a later period, beautiful carving of all sorts of gems was wonderfully developed. It must have required a long time to produce some of the carved pieces. The Babylonians polished *chalcidony* in the Third Dynasty (date unknown).

THE COPPER AGE

Archeologists have not been agreed as to whether there was a copper age or not, but recent archeological discoveries in Egypt and southwestern Asia would seem to have settled the matter in the affirmative. Geological evidence shows that copper was available for use long before bronze; so, from the geologist's viewpoint, since a bronze age is recognized, a copper age should be, also. There is an excellent mineralogical reason for this belief. Pure metallic copper occurs naturally and is usually found at or near the surface. It is the only *common* metal occurring extensively in the native state (gold and silver, among the *rarer* metals, occur native) and is, therefore, most likely to have been found and utilized long before primitive man acquired sufficient metallurgical skill to extract copper and tin (ancient Egyptian bronze contained 88 parts copper and 12 parts tin) from their ores and alloy them.

We do not know when or where *copper* was first found. Some have placed the date of its discovery at 18000 B.C. or earlier. Man was certainly familiar with copper compounds very long ago, because green glazed beads and powdered *malachite* (copper carbonate) have been found with the Badarian cultures of 13000 to 12000 B.C. As native copper is often associated with the oxidized copper minerals, *malachite* and *azurite* (also a copper carbonate), it is very possible that it was found with the *malachite*.

We do not know which ancient nation first learned the method of extracting copper from its ores. The evidence is in favor of the Egypt-

tians, with the Babylonians (or the Cyprians) as another possibility. A camp fire built on an outcrop of copper ore (the heat and charcoal would readily reduce the carbonates of copper to the metal) might have led to the discovery of a source for copper and a method of extracting it. It is probable, however, that ancient men had sufficient mental ability to seek by experimentation a method of extracting the metal from its ores. We know that the Egyptians were familiar with the copper carbonates as early as 13000 to 12000 B.C. They could scarcely have failed to notice that their native copper implements changed to a green mineral like malachite and then to have sought to reverse the process and secure the metal from the malachite.

If Sir Flinders Petrie's Egyptian time scale be accepted, it was in 4800 B.C., in the reign of King Zoser of the Third Dynasty, that copper mines were being worked in the Sinai Peninsula just across the Red Sea from Egypt. Malachite was apparently the chief mineral in these mines (at least, it is the chief one seen in the old workings today). Some men have suggested that it was largely used in making colored glazes. Although this is a possible use, the presence of slag dumps about the old mines indicates that a metallurgical treatment of some kind was known at that time.

The great King Snefru, first ruler of the Fourth Dynasty (4700 B.C. according to Petrie), opened a new mine "for copper and malachite at Wadi Maghara," not far from Mount Sinai. On a rock near these mines is found his emblem. In the Sixth Dynasty, likewise, the mines were worked, as the emblem of King Pepi I of that dynasty is on them, also. The question arises as to whether native copper was found in these mines, but there is no answer. They were evidently a source of copper down to the time of Rameses III, Twentieth Dynasty, when they were probably abandoned.

The dates given above appear to be fairly correct for Egypt, but there is much more uncertainty as to the period when Babylon first used copper. Cast copper figures from Tell Obeid (about 3000 B.C.) are in the British Museum. Copper was used in covering figures at a still earlier period. The source of that employed by the Babylonians is unknown, but it may have come from Asia Minor, the island of Cyprus, the Sinai Peninsula, or the Far East.

The island of Cyprus (from which the word *cuprum* was derived) furnished copper at a very early period (tentatively about 4000 B.C.). Slight evidence of neolithic man is found there. The Cyprus copper mines were probably worked before those in Syria and on the Ægean Islands. Whether this antedated the use of the metal by the Egyptians is not known. The possession of these valuable mines was not an unmixed blessing to the Cyprians, for their country was several times under the control of different nations as a result of their presence.

The Chinese probably knew of the use of copper at a very early date. There are numerous copper- and tin-producing areas in China, and they have long been worked. The earliest authentic date of such workings, however, is about 2500 B.C.

Knowledge of the uses of copper had become widespread in Europe by about 4000 B.C. Copper being easily worked was well adapted to a wide range of uses, such as utensils, weapons, ornaments, and decorations.

Occasional newspaper stories today tell of the hardening of copper and refer to it as a lost art with the inference that the ancients were able to temper it. Some men think that phosphorus was used to make it hard and that it has been leached out subsequently. As a matter of fact, this assumption is without any basis. There is no reason to believe that copper has ever been tempered.

After its discovery, the use of copper by man never entirely ceased, even when bronze and iron became common; and today, copper production has assumed gigantic proportions due, in large part, to its use in the electrical industry. The total production for the world in 1928 was 1,883,422 short tons. If this amount of copper were converted into common size-14 wire, it would extend 54,843,916 miles—enough to go around the world 2,194 times or to reach over halfway to the sun.

THE BRONZE AGE

Bronze, an alloy of copper and tin, gives its name to the period following the copper age and was the third material extensively used by man for weapons and the fourth for utensils. How ancient man first made bronze is unknown, but there are two views. One is that malachite and *cassiterite* (tin oxide) were smelted together. That this is possible has been proved experimentally. The other is that each metal was smelted separately and then mixed. On account of the evident metallurgical skill that had already been shown in smelting copper, this view seems feasible. Some tin veins contain copper minerals; and, although such veins are not common, it is possible that the first bronze was made from a natural mixture of minerals of the two metals.

The oldest piece of bronze that has been discovered was found in the pyramid of King Snefru, near Medum, Egypt. Its date is about 4700 B.C.¹ As stated before, King Snefru had mined and smelted copper on the Sinai Peninsula. His nearest source of tin (as far as is known) was Cornwall in the British Isles. There is no evidence that the Cornwall mines were worked before 2000 B.C. (which is about the date of the bronze age in Britain); hence, the source of the tin in the bronze piece dating to 4700 B.C. is unknown.

The uses of bronze were similar to those of copper, except that, since the former is harder, it was more extensively employed for weapons.

¹ Petrie.

Many bronze articles have been found in various parts of Europe—more than copper, since it is more durable. It is the magnificent Greek and Roman bronzes that give us such a fine record of the artistic products of those periods, though these belong to the more recent history of man.

THE IRON AGE

Some archeologists believe that *iron* was known to primitive man before copper and that the evidence of such knowledge has disappeared. This is not very probable, since native iron is practically unknown, and native copper is relatively common. Iron was known in Egypt about 4700 B.C. and in Assyria and other places not long afterward. Pieces of iron wire were found in the pyramids of the Gizeh group (Fourth Dynasty, about 4700 B.C.) and in the pyramids of Abusir (Fifth Dynasty), and iron is mentioned in one of the funeral texts that adorned the chamber of the pyramid walls of Pepi I (Sixth Dynasty). Very little iron is found, however, in Egyptian tombs, due, it is thought, to the idea that the metal was impure and, therefore, out of place in tombs. The Assyrians were probably the first people to become skilled in the working of iron. This may have been because they had little copper.

By 2000 B.C., the knowledge of iron was widespread, and by 1000 B.C. the people of most nations had become highly skilled in iron working. As their art in hardening it increased, the use of bronze for common utensils and weapons decreased, until finally iron was the metal most widely used. It was far more abundant than the other metals, easy to extract from its ores, and easy to work into various articles.

A fondness exists for calling the present age by various names; but, if the absolutely essential material is considered, we are still living in the iron age and will continue to do so for some time. The world produced 189,231,840 short tons of pig iron and crude steel in 1926.

OTHER MATERIALS MADE USE OF THROUGH THE AGES

Though the names of the ages just discussed have been based upon the principal material in use during each period, it must not be thought that other minerals were not used, also.

Gold.—Gold has long been regarded as the first metal known to man. This assumption is well founded, for the following reasons: it occurs in the metallic state, is heavy (18 to 20 times as heavy as water), never tarnishes, and is not attacked by the common solvents. Because of its weight and insolubility, it is readily concentrated in sands and gravels along streams. Its occurrence is widespread, though it is rarely found in large amounts. Both the physical properties and occurrence of gold favor the view that it was known before copper (although there is no evidence that it was). Its scarcity being what it is, no age has ever been called a gold age.

It is claimed that gold was known in the Fourth Dynasty in Egypt. A gold fly was found in a cemetery of the Eleventh or early Twelfth Dynasty in Fayum, Egypt. During the Twelfth Dynasty, King User-tesen II conquered a large part of Nubia and took possession of the gold mines of that country. As this gold had to be extracted from its ores, it is evident that the Egyptians were familiar with the metallurgical processes necessary for the purpose. The Babylonians and Assyrians, likewise, were probably familiar with this metal and able to obtain it from its ores. Thus, the historical evidence also points to a great antiquity for man's knowledge of gold, and it may well have been the first metal known to him.

The physical properties of gold early endeared the metal to its discoverers, and the desire to possess it has remained with the human race to the present day. The tremendous influence which it has exerted upon man cannot be measured, and unfortunately the influence has not always been beneficial. The search for gold has led man into torrid, desert, and frozen regions.

Silver.—Silver was doubtless found and used at about the same time as gold. It also occurs native, usually in association with gold. Being less durable, it does not occur so commonly in the free state. It has never been prized so highly, though it has always been considered valuable. It was called *white gold* by the Egyptians. The amounts of gold and silver possessed by some of the kings in the period preceding the Christian era must, if reports be true, have been enormous. King Solomon was tremendously rich, and there is still much speculation as to the location of his mines, conflicting evidence having placed them in both Africa and Asia.

Lead.—Lead was used by ancient man, but the date of its discovery is unknown. Silver is usually associated with lead ores, so the metal probably had an early discovery, also, as some of this type of ore was sure to have been found. Egyptians are said to have worked argentiferous lead and iron mines near the Red Sea and at Jabal Rossas.

Lead was mined at several points in southwestern Asia and, also, in the Far East. When the Phœnicians, in 1100 B.C., crossed the Mediterranean and reached the site of Cadiz, they found the natives of the region possessing gold, silver, copper, and lead. These they obtained from mines in the interior of their country. The metals furnished material for trade relations. The Phœnicians located and mined lead ores in Cyprus, the Ægean Islands, and other regions. It was probably through them that various metals were interchanged among the ancient peoples, especially between 1000 B.C. and the Christian era.

The first known use of lead was as a solder and dates back to an early period in Egyptian history. The Romans used great quantities in making their water systems and in building operations. They secured some from

mines in several parts of Great Britain. Although never regarded as an especially valuable metal, lead has had a constant use by most peoples. The amount used today is very large. Lead was third in value of the metals produced in the United States in 1928.

Stone as a Building Material.—We have no evidence that man had ever made use of stone as a building material in the stone age; but, as far back as 5000 B.C., the Egyptians had done so. The pyramids of about that period are evidence of their skill in this respect, for they employed granite as well as sandstone. The use of such a fine, durable building material as stone became widespread and has continued down to the present day.

THE UTTER DEPENDENCE OF MODERN CIVILIZATION ON EARTH MATERIALS

From the early uses of a relatively few materials, man has progressed, until, today, there is scarcely a mineral occurring in sufficient abundance which he does not utilize. The materials already discussed still remain important in his economic life, but others have been discovered which also have a vital place.

The uses of earth materials are as varied as are the activities of man. Every moment of life, we are in some way influenced or aided by one or more of them. Most men know a little, in a vague way, about the source and origin of these substances and the method of obtaining or preparing them for use. That coal, gold, iron, lead, and other such materials are mined, that rock is quarried, or that oil is drilled for is quite generally known, and a more or less authentic knowledge exists concerning where these substances are found; but, as to any accurate information about these processes or about the nature of the substances, the average man possesses little.

A few of these materials and our points of contact with them may be mentioned. We find concrete in the walls and floors of our basements, in the walls of large buildings of many types, in our driveways, sidewalks, roads. Few know the materials that go into the making of cement or that their value annually in the United States is over \$275,000,000. Yet a knowledge of even a material so humble as cement adds not only to our information, making us more intelligent, but, also, surely, if we view the matter rightly, to the interest, the adventure, the glamor of life. Likewise, shall we be interested and benefited to have definite information about the making of brick; the quarrying of building stone and of decorative stones, such as marble or serpentine; the making of glass; of paint; of tile. These products are all made from earth materials and are encountered by us daily in the construction of the houses in which we spend a large part of our existence. In the furnishing of houses, in ornaments for our clothes, in the vehicles we ride in, we make further use of

earth materials or products manufactured from them. Countless numbers of these substances are required by the industrial world, the business world, and the medical profession, and all of them sooner or later affect our individual lives.

Thus, we see that the use of earth materials, begun by primitive man, has come to occupy an essential place in modern civilization. Man today makes the numerous minerals and rocks contribute to his pleasure, comfort, and well-being, just as did his primitive ancestor before him.

CHAPTER III

GENERAL PRINCIPLES OF THE FORMATION OF MINERAL DEPOSITS

INTRODUCTION

Any aggregate of a single mineral or of several minerals, irrespective of size or shape, is a *mineral deposit*.¹ For the purposes of this volume, the term "mineral deposit" will include any earth material, whether it is *solid*, *liquid*, or *gaseous*. Therefore, rocks, water containing various substances in solution, petroleum, and gas are mineral deposits. To understand the following discussion of the principles governing the methods of formation of these various types of mineral deposits, it is essential that the scope of the term be clearly understood.

A *mineral* is a naturally occurring inorganic substance having (within limits) a definite chemical composition and definite physical properties. This definition is not perfect, as it is impossible to make a perfect one applied to natural objects, for there are few sharply drawn lines in nature. For our purposes, it will answer very adequately, however.

A single mineral may occur in large masses, such as the calcite comprising limestone, the quartz in sandstone, and thick beds of salt and gypsum; but the majority of mineral occurrences are aggregates of more than one mineral. These aggregates of one or more minerals are commonly known as *rocks*. A rock may also be defined as an essential part of the earth's body (or crust). Either of these definitions is satisfactory, but in this book the emphasis will be placed upon the rock as an aggregate of one or more minerals; and, as such, it is a mineral deposit.

Minerals also occur in other forms, such as masses in veins or cavities or as scattered particles in a rock. These occurrences are infinite in number and of widespread distribution. They are of all sizes, ranging from microscopic particles to deposits miles in length. Few are of economic importance, but all are interesting as mineral deposits.

Few questions are as far-reaching or as important as those concerning the *origin of mineral deposits*. Rocks compose the earth's body; and rocks,

¹ The name "mineral deposit" is preferred to "ore deposit," because an *ore deposit* is commonly regarded as a concentration of economically valuable metalliferous minerals, whereas *mineral deposits* include all mineral aggregates irrespective of value. *Ore* is that part of a mineral or ore deposit that can be profitably extracted. As the market value controls whether a mineral will pay for its extraction, it will be seen at once that what is ore today may be a worthless material next week.

as defined above, are mineral deposits. The question of their origin, therefore, raises the larger one of the origin of the earth. It is impossible to investigate that topic here, but the general composition of the earth's body is discussed, for the mineral deposits dealt with later had their origin in the minerals of the earth's body. We readily accept this fact, but *how* the deposits were formed is what we must explain. Many questions immediately present themselves: as to how the minerals were collected, transported, and deposited in their present position; how they came to have their present form; why different metals and different minerals are associated; why some deposits are richer than others. These and many other questions must be answered if we are to explain the mode of formation of a mineral deposit.

It is hardly necessary to say that the complexity of the problem leads us beyond our present-day knowledge. The minerals of these deposits were formed according to definite and fixed chemical and physical laws; and, though we possess a vast storehouse of knowledge about these laws and use the knowledge to the best of our abilities, we are still unable to account for all the phenomena in connection with mineral deposits. Progress has been made, and we can safely say about a great many deposits that they were formed by this method or by that. There is still, however, much work to be done, and the rate of advance is slow, much slower than many are willing to admit. And, of course, where we are dealing with the application of fixed laws whose operation is not fully understood (for who has worked in the laboratory with pressures equal to those at 50 miles beneath the earth's surface or with the temperatures found there or at even lesser depths?), there is always the element of interpretation by man himself. And men do not agree.

Thus, in summing up our problem: we have a vast store of physical and chemical facts that must be used in working out the origin of mineral deposits, but the application of these facts is not always clear, and, therefore, it is sometimes necessary to build up theories to finish the story of origin.

The student of mineral deposits will find their origin a fascinating study, if he will seek to follow each successive step in their formation. This will call for a knowledge of mineralogy, geology, physics, chemistry, and other related sciences and, last, but not least, the ability mentally to visualize a series of past events occurring, for the most part, far beyond the possible reach of the human eye. In this brief volume, there is no place for details and very little for a comparative analysis of different theories. For the student who wishes to go farther into the subject, the longer and more exhaustive treatises are recommended.

The discussion of the principles of mineral formation, which follows, is a presentation of an ideal sequence of events. This ideal sequence should enable the student to follow more closely the genetic relationships

of mineral deposits and to obtain a better picture of mineral formation. The discussion begins with a brief consideration of the physical state of the earth and its composition. Following, there are discussions of magmas, the changes they undergo, the mineral deposits arising from the changes, and the subsequent alterations of these deposits attended by the formation of new deposits.

THE EARTH

The earth is a spheroid, having a radius of 3,958.8 miles. It has a surface area of 196,944,000 square miles, 55,000,000 of which is land. Its volume is 260,000,000,000 cubic miles.

The Physical State of the Earth.—The physical state of the interior of the earth has long been a matter of speculation. Under the older concept of its origin, the earth was regarded as a liquid mass with a solid crust. This crust, as computed by various investigators, was too thin to maintain the stability which we know it possesses. The facts now known about the earth indicate that it is a body possessing a high degree of rigidity: from one and a half to two and a half times the rigidity of steel. This has been determined by measuring the rate at which earthquake vibrations pass through the earth. In spite of this great rigidity, the earth is subject to a slight distortion by the pull of the sun and the moon and to a greater distortion by its rotation on its axis. Whether the rigidity of the earth means that it is completely solid is not known, but, in general, it is believed to be solid. The term “crust” as used today is an inheritance from this early belief in the liquid condition of the interior of the earth. As used in this volume, “crust” will indicate merely the outer part of the earth.

The pressure at the center of the earth is enormous: 45,000,000 pounds to the square inch. The temperature is wholly a matter of conjecture. The rate of heat increase downward in numerous deep borings and mines has been measured and is commonly quoted as $1^{\circ}\text{C}.$ for 100 feet. Calculating the temperature at the center of the earth from this rate of increase gives such enormous figures that most men doubt the correctness of the rate. Estimates have been made that are as high as $100,000^{\circ}\text{C}.$, but a more recent figure is $20,000^{\circ}\text{C}.$, and still lower ones are given.

The molten materials ejected from volcanoes are regarded as having their source relatively near the surface. The independence (observed long ago) of volcanoes from each other, though located close together on the earth's surface, indicates that there is no universal liquid substratum but that each volcano has its own independent reservoir. The distribution of these liquid areas (magmas), as suggested by Chamberlin, is shown in Fig. 3.

The Composition of the Earth.—The composition of the earth's body has long been a matter of interest and speculation. In recent years, several men have studied the problem in the light of extended knowledge of the physical condition of the earth and have obtained very interesting results.

The average specific gravity of the earth is 5.5; that of the surface rocks is 2.75; therefore, it is evident that the interior, having a smaller volume, must be composed of heavier materials. Iron is the heaviest common metal in the outer part of the earth's body and so is believed to be still more abundant below. Nickel is universally associated with

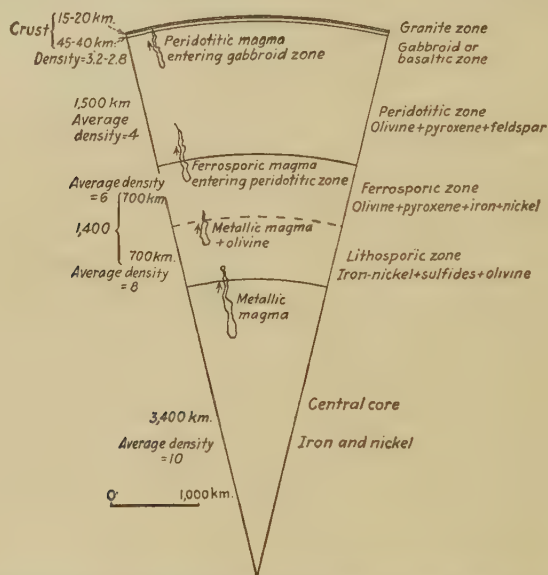


FIG. 3.—Ideal section of the earth showing the zones, as estimated by Washington, and magmas from lower zones penetrating those above, as suggested by Chamberlin.

all the occurrences of metallic iron (those in meteorites and the one known occurrence in the rocks of the earth, in Greenland) and so is regarded as being abundant also in the earth's interior. Especially is this thought to be true because nickel is still heavier than iron. Likewise, iron and nickel are the only common metals in meteorites, which are regarded as representative of the material of which the earth was formed. As several investigators arrived independently at similar results, it is generally accepted that there is this core of iron and nickel and smaller quantities of other heavy metals in the interior of the earth.

Proceeding outward from this denser inner core, a constant decrease in specific gravity takes place until the specific gravity of 2.75 is reached in the outer shell. A constant increase in the amounts of the lighter elements, oxygen, magnesium, silicon, aluminum, calcium, sodium, and

potassium, accompanies the decrease in specific gravity. The change in density undoubtedly is due to this concentration of lighter elements at the surface.

Zonal Arrangement of the Constituents of the Earth.—Several men in recent years have computed the chemical composition and the distribution of the elements within the earth. There is remarkable agreement as to the results obtained; and, as the source of the elements in mineral deposits is of interest in economic geology, an outline of the zonal distribution will be given. Among those who have discussed the problem are Adams and Williamson, Clarke, Daly, Washington, Wiechert, and Goldschmidt. The zonal distribution, as outlined by Washington,¹ is given here (see Fig. 3).

The Inner Core.—The center of the earth is assumed to be an iron-nickel core because the specific gravity of the earth, as a whole, demands it (see Fig. 4). It is probable that limited amounts of other metals, such as chromium, vanadium, copper, cobalt, platinum, iridium, and osmium, and of sulfides, phosphides, carbon and even carbides occur in this zone, also. The specific gravity of the core averages about 10; its radius is about 3,400 kilometers; and it comprises about 27.3 per cent of the earth's mass.

The Lithosporic Zone.—The metallic core grades into the next zone, the lithosporic (*i.e.*, containing sporadic rock material), in which there is

an increasing amount of magnesium and silica occurring as the mineral olivine. The olivine increases in amount upward, accompanied by a corresponding decrease in the iron-nickel content, until at the top of the zone they are present in about equal proportions. The lithosporic zone is the richest zone in sulfides. These sulfides include those of lead, copper, zinc, iron, cobalt, nickel, silver, and manganese. The zone is estimated to contain 1.82 per cent sulfur. It seems to the author of this volume that this estimate is too low, as are probably the majority of our esti-

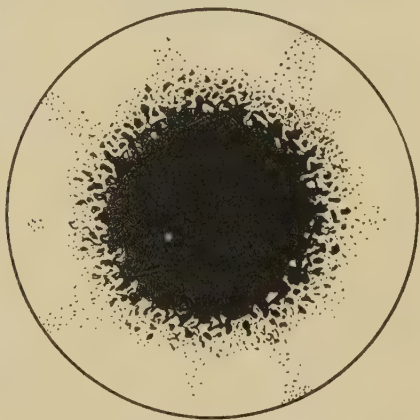


FIG. 4.—Cross section (drawn to scale) of the earth, showing the probable metallic iron-nickel core; the transition zone of mixed iron and nickel, sulfides, and silicates; the peridotite zone with iron and nickel and sulfides scattered through it; and the outer 60-kilometer crust represented by a line (drawn to scale). (*Modified from Adams and Washington, Jour. Wash. Acad. Sci.*, vol. 14, 1924.)

¹ WASHINGTON, H. S., The Chemical Composition of the Earth, *Am. Jour. Sci.*, 5th ser., vol. IX, pp. 351–378, 1925. Washington has published several other papers dealing with the chemistry of the earth's body, but references to them, as well as to the work of the other men, are given in the one just cited.

mates for sulfur in rocks and meteorites, a point noted by Washington. Goldschmidt,¹ in his scheme of the distribution of the earth's materials, postulates a distinct sulfide zone about 1,700 kilometers thick. Such a volume of sulfides is undoubtedly too high an estimate, just as Washington's is probably too low. The amount of sulfides in the lithosporic zone and the one above it should probably be increased twofold or threefold over Washington's estimate. This figure would even then be far below Goldschmidt's. The average density of the zone is 8; its thickness is about 700 kilometers; and it represents 8.51 per cent of the earth's mass.

The Ferrosporic Zone.—The lithosporic zone grades into the ferrosporic (*i.e.*, containing sporadic metallic iron and nickel) in which olivine, enstatite-hypersthene (pyroxene), and a little feldspar occur. The iron-nickel content has decreased to about 10 per cent, or less, near the top of the zone. The sulfides, phosphides, and carbon are less in amount than in the zone below. Sulfides are more abundant than the other two compounds. The ferrosporic zone has an average density of 6, a thickness of about 700 kilometers, and represents 22.55 per cent of the earth's mass.

The Peridotitic Zone.—The ferrosporic zone grades into the peridotitic zone which has increasing amounts of ferromagnesian silicates (chiefly pyroxenes) and basic feldspar (chiefly labradorite) and contains some olivine. The metallic iron and nickel and the sulfides are present only locally. Oxides, especially magnetite and chromite, are more abundant. The peridotitic shell has an average density of 4, is about 1,500 to 1,540 kilometers thick, and comprises 40.08 per cent of the earth's mass.

The Crust.—Above the peridotitic zone is the crust of the earth, a shell estimated at 60 to 100 kilometers in thickness. The lower figure, for many reasons, is probably more nearly correct. The crust is divided into two layers; the lower, known as the "gabbroid" (also, as the "basaltic" or "subcrust"), is from 40 to 45 kilometers thick; and the upper, known as the "granitic" (commonly as the "crust"), is about 15 to 20 kilometers (10 or 12 miles) thick.

The *gabbroid layer* consists dominantly of pyroxene and a soda-lime feldspar, which approximates labradorite in composition. A little olivine and magnetite are present. Small amounts of sulfides are present locally. The average density of the layer is 3.2, and it represents only 1.08 per cent of the earth's mass.

The *granitic layer* has the composition of the granitic types of rocks. The alkali feldspars and quartz are abundant and are accompanied by mica and hornblende. This layer, as well as all those below, contains injections of materials from the zones below them. This gives rise to

¹ GOLDSCHMIDT, V. M., *Science Progress*, vol. XIX, p. 546, 1925.

various intermediate types of rocks. Where the injected magma is rich in metals, valuable mineral deposits may result.

Vertical Distribution of the Elements.—Washington¹ points out the distribution of the elements that accompanies the zonal distribution of the earth materials. *Metallic iron*, which is the dominant constituent of the core, decreases in amount to practically nothing at the surface; the one or two occurrences of native iron there being insignificant. Beginning in the lithosporic zone, iron unites with magnesium to form the silicate olivine. The two elements are at a maximum in this zone, and both decrease outward. *Metallic nickel* disappears in the ferrosporic zone, the nickel of the peridotitic zone occurring largely in the olivine or sulfides. *Oxygen* is not present in the core but appears in the lithosporic zone as the second most abundant element and becomes the leading element in the next zone, a position it holds to the surface. *Silicon* appears in the lithosporic zone and steadily increases to the surface, reaching its maximum in the granitic zone. *Magnesium* reaches a climax in the lithosporic and ferrosporic zones and decreases outward. *Calcium* and *aluminum* appear near the top of the ferrosporic zone and reach their greatest abundance in the gabbroid layer, where the calcium pyroxenes and labradorite are the most abundant minerals. Calcium falls off rapidly in the granitic shell, and its place is taken by the alkalies sodium and potassium. Aluminum shows only a slight decrease in the granitic shell. Of the alkalies, *sodium* had appeared in the ferrosporic shell, decreased slightly in the peridotitic, and then increased steadily to the surface. *Potassium* increased steadily from the ferrosporic shell to the surface. The shift in the amounts of the elements was accompanied by appropriate mineral changes in each zone.

It must not be thought that the various zones have a uniform composition, for such is not the case. They vary widely, largely because of a constant upward shift of certain minerals and a downward drift of others. The upward movement of a magma from a lower zone into a higher zone is illustrated in Fig. 3. The constant upward movement and reworking of the earth materials finally shifted the lightest ones to the crust, the very lightest, the water and gases, forming the hydrosphere and the atmosphere. Washington's estimate of the composition of the entire body of the earth is given in the following table:

¹ WASHINGTON, H. S., The Radial Distribution of Certain Elements in the Earth, *Jour. Wash. Acad. Sci.*, vol. XIV, p. 435, 1924.

TABLE 1.—ESTIMATED COMPOSITION BY ELEMENTS OF THE ENTIRE BODY OF THE EARTH¹

Element	Percentage	
Iron (metallic).....	31.82	} 39.76
Iron (in silicates).....	7.94	
Oxygen.....	27.71	
Silicon.....	14.53	
Magnesium.....	8.69	
Nickel.....	3.16	
Calcium.....	2.52	
Aluminum.....	1.79	
Sulfur.....	0.64	
Sodium.....	0.39	
Cobalt.....	0.23	
Chromium.....	0.20	
Potassium.....	0.14	
Phosphorus.....	0.11	
Manganese.....	0.07	
Carbon.....	0.04	
Titanium.....	0.02	
Total.....	100.00	

¹ WASHINGTON, H. S., *Am. Jour. Sci.*, vol. IX, p. 361, 1925.

Composition of the Earth's Crust.—We are fairly well acquainted with the composition of the earth's crust, for rocks that were once at depths of many miles are now available for study, due to the folding, faulting, and erosion of the crust. About 5,000 analyses of igneous rocks from all available parts of the crust of the earth have been tabulated and the average composition computed. Of especial interest in the study of economic geology are the estimates as to the quantities of the minor constituents. The average composition of the igneous rocks of the outer 10 miles of the earth's crust, as compiled by Clarke and Washington, is given in the table below:

TABLE 2.—THE ESTIMATED AVERAGE COMPOSITION BY ELEMENTS OF THE EARTH'S CRUST¹

Element	Percentage
Oxygen.....	46.710
Silicon.....	27.690
Aluminum.....	8.070
Iron.....	5.050
Calcium.....	3.650
Sodium.....	2.750
Potassium.....	2.580
Magnesium.....	2.080
Titanium.....	0.620
Hydrogen.....	0.140
Phosphorus.....	0.130
Carbon.....	0.094
Manganese.....	0.090

¹ CLARKE and WASHINGTON, U. S. Geol. Survey *Prof. Paper* 127, p. 34, Table 17, column 3, 1924.

TABLE 2.—THE ESTIMATED AVERAGE COMPOSITION BY ELEMENTS OF THE EARTH'S CRUST (*Continued*)

Element	Percentage
Sulfur.....	0.052
Barium.....	0.050
Chlorine.....	0.045
Chromium.....	0.035
Fluorine.....	0.029
Zirconium.....	0.025
Nickel.....	0.019
Strontium.....	0.018
Vanadium.....	0.016
Cerium, yttrium.....	0.014
Copper.....	0.010
Uranium.....	0.008
Tungsten.....	0.005
Lithium.....	0.004
Zinc.....	0.004
Columbium, tantalum.....	0.003
Hafnium.....	0.003
Thorium.....	0.002
Lead.....	0.002
Cobalt.....	0.001
Boron.....	0.001
Glucinum.....	0.001
Total.....	100.000

As shown by the table, only 8 elements are present in the earth's crust in amounts exceeding 1 per cent, and these 8 total to 98.58 per cent. No less than 29 elements are included in the remaining 1.42 per cent. Valuable (to man) metals, such as silver, gold, tin, mercury, and platinum, do not appear in the list at all. Various estimates have been made as to the quantities of these rare elements in the earth's crust, and one of these, made by Clarke and Washington, is given in the following table:

TABLE 3.—ESTIMATES OF THE AMOUNT OF RARE ELEMENTS IN THE IGNEOUS ROCKS OF THE EARTH'S CRUST¹

Element	Percentage
Molybdenum.....	0.000X
Rubidium.....	0.000X
Arsenic.....	0.000X
Tin.....	0.000X
Bromine.....	0.000X
Cæsium.....	0.0000X
Scandium.....	0.0000X
Antimony.....	0.0000X
Cadmium.....	0.0000X
Mercury.....	0.0000X
Iodine.....	0.0000X
Bismuth.....	0.00000X

¹ CLARKE and WASHINGTON, U. S. Geol. Survey *Prof. Paper* 127, p. 21, 1924.

TABLE 3.—ESTIMATES OF THE AMOUNT OF RARE ELEMENTS IN THE IGNEOUS ROCKS OF THE EARTH'S CRUST (*Continued*)

Element	Percentages
Silver.....	0.00000X
Selenium.....	0.00000X
Platinum.....	0.000000X
Tellurium.....	0.000000X
Gold.....	0.000000X
Iridium.....	0.0000000X
Osmium.....	0.0000000X
Thallium.....	0.0000000X
Indium.....	0.00000000X
Gallium.....	0.00000000X
Rhodium.....	0.00000000X
Palladium.....	0.00000000X
Ruthenium.....	0.00000000X
Germanium.....	0.00000000X
Radium.....	0.000000000X

Although the estimates by Clarke and Washington are small, they are believed by Berg to be too high. Berg's estimates for the amounts of some of the economically important rare metals in the earth's crust are given in the following table:

TABLE 4.—ESTIMATES OF THE AMOUNTS OF SOME OF THE ECONOMICALLY IMPORTANT RARE ELEMENTS IN THE EARTH'S CRUST¹

Element	Percentage
Copper.....	0.010
Zinc.....	0.006
Lead.....	0.0008
Molybdenum.....	0.0006
Tin.....	0.0005
Arsenic.....	0.00045
Antimony.....	0.000025
Cadmium.....	0.000010
Silver.....	0.000004
Bismuth.....	0.000003
Mercury.....	0.0000025
Gold.....	0.0000001
Platinum.....	0.000000008
Iridium.....	0.00000000025
Palladium.....	0.00000000008
Radium.....	0.000000000002

¹ BERG, G., *Zeitschr. prakt. Geologie*, vol. V, pp. 73-79, 1925.

The estimates of the rare metals are very significant in our study of mineral deposits, as we shall be interested in accounting for deposits of lead, zinc, copper, gold, silver, molybdenum, and other metals; and, if the average igneous rock at the surface contains only mere traces of them, it makes our problem of accounting for the origin of the deposits all the more interesting and complex.

Berg's estimates are probably more nearly correct than those of Clarke and Washington, as anyone who has carefully studied large quantities of all kinds of rocks can readily believe, for evidences of these metals are much less than just "rare." All these estimates are based upon very inadequate data, for 5,000 or 25,000 analyses of rocks can be of little value when the total quantity analyzed is only a few hundred pounds.

MAGMAS

Magmas are masses of molten rock within the earth's crust. Their temperature has been estimated by Larsen¹ as 600 to 700°C. for rhyolitic magmas and 800 to 900°C. (a very few as high as 1,260°C.) for basaltic magmas. The composition of magmas is as variable as the materials that constitute the earth. Some, especially those of the granitic types, are rich in gases and metals of various kinds, but not all, or even a large percentage, necessarily contain important quantities of these rarer elements. The volume of magmas is unknown; but, judging from the size of known occurrences of great igneous masses at the surface, some of the magmas attained dimensions measured in tens and hundreds of miles. Their cubic contents must have been enormous. From such large masses, they range down to those of small size having just sufficient heat to remain liquid and be able to move.

Movement of a Magma.—Magmas have undoubtedly moved outward from the interior of the earth. This movement is accomplished (1) *by melting and assimilation* of the overlying rock (probably the more important method for deep-seated magmas) and (2) *by earth movements* which, aided by the pressure of the gases within the magma itself, forced it to flow through the rocks.

The dominant direction of movement is upward, hence the vertical elongation of magmas shown in Fig. 3. Melting of adjacent rocks could occur on all sides of the magma chamber but should be more rapid at the top, because the pressure is less there than on the sides and, also, because most of the gases (which aid greatly in solution work) would be in the upper part.

After the magma reaches the outer zone where fractures exist, such openings would be followed. In this fracture zone, the "stopping" method, of Daly, would also take place. By this method, the magma pries off solid blocks from the roof; and, as these sink, the liquid moves up to take their place.

When the heat available for melting was used up or where the pressure was insufficient to force the magma upward, movement would cease, and the magma might eventually become solid. New accessions of heat would permit remelting and the renewal of the upward movement.

¹ LARSEN, E. S., The Temperatures of Magmas, *Am. Mineralogist*, vol. XIV, p. 94, 1929.

CONSOLIDATION OF A MAGMA

Whenever the temperature of a magma falls below the point of saturation for any constituent, that mineral will crystallize out; for the chemical laws that apply to a solution in a test tube are equally in control in a magma. The continued lowering of the temperature would eventually result in complete solidification.

Order of Crystallization.—The detailed study of rocks has revealed to us a fairly definite order of crystallization in a magma.

First Steps in Crystallization.—The first substances to solidify are usually the minor constituents that are relatively insoluble in such a silicate solution as that forming the magma. These are commonly known as “accessory minerals.” They include *apatite*, $\text{Ca}_5\text{F}(\text{PO}_4)_3$; *zircon*, ZrSiO_4 ; *titanite*, CaTiSiO_5 ; the sulfides: *pyrrhotite*, Fe_7S_8 , and *pyrite*, FeS_2 ; and the oxides: *rutile*, TiO_2 , *ilmenite*, FeTiO_3 ; *magnetite*, Fe_3O_4 , *chromite*, FeCr_2O_4 , *hematite*, Fe_2O_3 , and *corundum*, Al_2O_3 . Some of these minerals are more abundant in granitic rocks; others, in syenitic; and others, in basic rocks, such as gabbros, peridotites, and basalts.

Further Steps in Crystallization.—As the temperature of the magma continues to fall, other minerals reach their saturation points and crystallize out. In general, the *ferromagnesian minerals* (*pyroxenes*, *hornblendes*, *olivine*) come out next, followed, in turn, by *plagioclase feldspar*, *orthoclase*, and *quartz*. The crystallization of these minerals removes from solution most of the materials of the magma and gives rise to solid rock.

Final Stages of Concentration and Crystallization.—During the process of crystallization, however, the liquid and gaseous substances had been accumulating. These residual solutions are known as the *mother liquors*. The cooling and resultant solidification of the magma occurred on the outside first, so the gases and liquids were eliminated from that portion, largely toward the center; and, as solidification continued, they were forced still further inward and concentrated in the still-liquid portions of the magma. These liquids had permeated every portion of the magma, at first, and had taken into solution the minor quantities of metals and rare earths. Their concentration, therefore, gave rise to a gaseous solution, rich in substances that had the possibilities of forming economically valuable mineral deposits. Thus from the standpoint of economic geology, the mother liquors are the most important part of the magma. The substances had remained in solution to the final stages, either because they were present in too small quantities to be concentrated at first or because they were readily soluble in the magmatic solution.

The substances present in the final liquors depend upon the composition of the original magma. Certainly, various gaseous elements, such as are common in all lavas, would be present in the magma. These gases are *water vapor*, *chlorine*, *fluorine*, *boron*, *carbon dioxide*, *carbon monoxide*, *sulfur*, *hydrogen sulfide*, *arsenic*, *phosphorus*, and other substances. Vari-

ous metals might be present, such as *tin, tungsten, copper, iron, gold, silver, lead, and zinc*. Rare elements, such as *lithium, beryllium*, and the *rare earths*, are also common constituents; but all are not necessarily present in any one magma, nor are they present in similar quantities. Variability is the rule in the magma and in the resulting mother liquors.

The mother liquors will be, then, more or less concentrated solutions of the gases, metals, and rare elements, just mentioned; and, by various combinations of these constituents, they will give rise eventually to a *second group of accessory minerals*. This second group of accessories comprises numerous minerals, which form the largest number and the most valuable of our ore deposits.

Factors Causing Variations in the Order of Crystallization.—The method of solidification, just outlined, is subject to considerable modification, because various events, such as the movement of the magma during crystallization and the addition of more heat or new materials, would change the sequence. Also, chemical reactions might take place within the cooling magma that could change the normal order of crystallization. These are problems, however, for the petrologist and are not within the scope of this volume.

SPLITTING OR DIFFERENTIATION OF A MAGMA

One of the most fundamental problems in the study of rocks is that of determining the origin of the different rock types. Petrologists believe that they are the result of the splitting of an original magma into two or more parts, different minerals going into the different parts. This splitting, likewise, is of importance in economic geology, for it produces not only the various types of rocks but also important ore deposits.

Possible Methods of Differentiation of Magmas.—In order to account for the splitting of magmas, several theories have been advanced, of differing degrees of application. These theories are:

1. Differentiation due to limited miscibility of liquids.
2. Differentiation by gravity during crystallization.
3. Differentiation by diffusion during crystallization.
4. Differentiation by absorption or assimilation.
5. Differentiation by squeezing out the liquid from a partly crystalline magma.

Differentiation by Limited Miscibility.—Differentiation of magmas through immiscibility (inability of substances to mix with each other; for example, oil and water) is of importance in determining the origin of ore deposits but is less important in studying the origin of the rock types. Most of the different rock silicates are capable of mixing with one another in all proportions, but this is not true of sulfides and silicates. If liquid sulfides and liquid silicates are mixed and allowed to stand, the liquid sulfides, being heavier, settle to the bottom, and the silicates go

to the top. This method of separation is well illustrated in a copper furnace, where the matte (a copper-iron sulfide) settles to the bottom of the furnace, and the slag (a silicate melt) floats on top. That the separation is complete is shown by the very low copper content of the slag.

Where iron and magnesium are present in considerable amounts in the liquid silicate magma, the solution is capable of dissolving some sulfides; hence, pyrite is commonly present in gabbros, peridotites, and basalts and much less so in granites.

The zonal arrangement of the earth is believed to be due to this separation of the various materials within it. The metals have gone downward to the centrosphere or core (Fig. 4). Surrounding the core is a transition area of metals, sulfides, and silicates. The outer zones consist of silicates with minor amounts of metals and sulfides. Intrusions of materials from below into overlying zones would enrich those zones with materials from lower ones. Thus, sulfides might be intruded into the peridotitic zone; but, if at some later time, the intruded area was melted, the lack of miscibility would again bring about a separation, the heavier sulfides settling downward toward or into the lower zones. Masses of sulfides found near the surface are the result of the splitting of a magma in the final stages, after its journey upward.

Differentiation by Gravity during Crystallization.—The possibility of separating a liquid mass into two different rock types during crystallization by the heavier crystals settling to a lower level and the lighter rising was early suggested to students of petrology. Although there is no agreement as to the extent to which the process has taken place, it is generally believed that, under favorable conditions, it may be an effective means of separation of a magma. This method, also, appears to be of more value in accounting for the formation of ore deposits than of rock types; for, as the specific gravities of the silicates are not markedly different, they would not be readily separated by gravity.

An instance of separation by gravity occurs in the case of the first-formed group of accessory minerals (named above). These minerals have specific gravities above those of the associated silicates, some of them very much above. Where a magma is rich in these minerals, their early crystallization would be followed by settling and accumulation at a lower level, due, of course, to the higher specific gravities of the minerals.

Differentiation by Diffusion during Crystallization.—The diffusion of a substance through a magma depends upon differences in concentration of the substance in different portions of the mass. This is operative principally at the outer part of the magma where cooling takes place first and crystallization starts. The crystallization reduces, at this point, the concentration of the solution for the substance which has crystallized, and thus immediately there begins a diffusion of particles of this substance

from inner parts of the magma where its concentration is higher. When, due to the diffusion, the saturation point of the mineral has again been reached in the cooling part, crystallization would result, and diffusion would start again.

As diffusion in the viscous silicate solution of a magma would be very slow, this method of separation probably is not very effective in forming ore deposits. A modification of the diffusion theory to take account of the convection currents in a magma, however, would probably show that diffusion is more effective. The hotter, more gaseous central portion of a magma is lighter than the cooler material along the walls; hence, the convection currents are rising in the center and sinking along the walls of the chamber (Fig. 5). This slow downward drift of the liquid

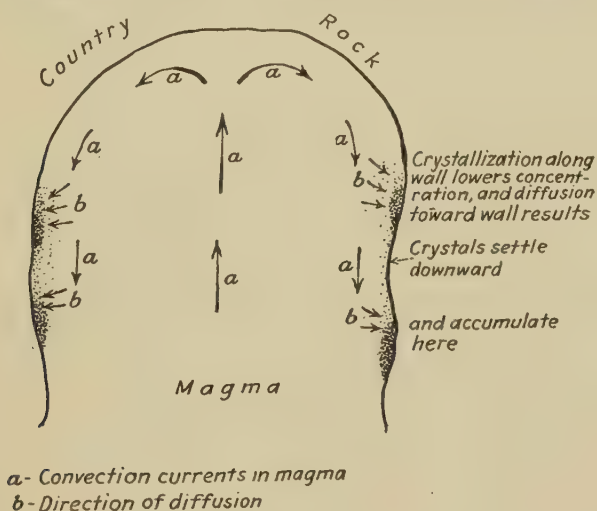


FIG. 5.—Sketch illustrating how the convection currents in a magma would be an aid in furthering the development of a magmatic segregation by diffusion.

past the zone of crystallization along the chamber walls would bring additional material near enough for diffusion to become effective. After crystallization (due to diffusion) had occurred, the further segregation of the minerals would be brought about by their immiscibility and by gravity.

Differentiation by Assimilation.—The assimilation of the adjacent country rock after it has been melted by the magma is thought to be a factor in producing different rock types and probably, ore deposits, also. During the upward movement of a magma, its constant melting of the overlying rocks would result in a great deal of assimilation and thus would bring about a marked alteration in the composition of the magma. It may be that this factor has been very effective in the formation of magmas rich in valuable metals, which later give rise to important ore deposits.

Near the surface, assimilation would be less effective in altering the composition of the magma, unless the assimilated rock was rich in some substance not abundant in the magma. For example, the carbon of diamonds may have come from an assimilated rock rich in organic carbonaceous materials.

Differentiation by Squeezing Out the Liquid from a Partly Crystallized Mass.—After a magma was partially crystallized and more or less of it was still in solution, an earth movement might crush the crystals together, squeezing out the liquid. This means seems to possess considerable possibilities for the formation of ore deposits, for the ejected liquid may, by concentration, have become rich in several metals; which, under the new conditions in the surrounding rocks, would be deposited.

The End Products of Magma Splitting.—The splitting of a magma normally gives rise to two end products: (1) the *igneous rocks* and (2) the *mother liquors*.

The Igneous Rock Types.—As a result of the splitting of a magma, the various rock-forming minerals—feldspars, micas, quartz, and ferromagnesian minerals—were segregated into aggregates that became the many varieties of igneous rocks. Although the number of different rock-forming minerals in a magma may be small, many varieties of rocks are formed as a result of their different combinations. These igneous rocks are, of course, mineral deposits and are used in large quantities as stone for building purposes. The most common of these rock groups are given in the following table (partly because the rocks are mineral deposits, and partly for future reference purposes):

TABLE 5.—THE COMMON ROCK TYPES AND THEIR MINERAL CONSTITUENTS

Mineral constituents	Rock types	
	Intrusive rocks (grained)	Extrusive rocks (dense)
Quartz and orthoclase.....	Granite	Rhyolite
Orthoclase.....	Syenite	Trachyte
Orthoclase and nephelite.....	Nephelite syenite	Phonolite
Orthoclase } and quartz.....	Quartz monzonite	Latite
Plagioclase }		
Orthoclase and plagioclase.....	Monzonite	Latite
Plagioclase (some orthoclase) and quartz.....	Quartz diorite	Dacite
Plagioclase and hornblende (and biotite).....	Diorite	Andesite
Plagioclase, pyroxene, and ($\pm$) olivine.....	Gabbro	Basalt
Plagioclase.....	Anorthosite	
Pyroxene and olivine.....	Peridotite	
Olivine.....	Dunite	

The Mother Liquors.—The final magmatic solution might contain any or all of the numerous substances of the magma. Usually, it contains only one or two minerals in abundance and small amounts of the others. Valuable ore deposits are rare in the earth's crust; therefore, the average magma must be low in valuable metals. The magmatic solutions are the only really effective means of segregating the valuable metals from the original magma, and thus to them we owe our important though widely scattered ore deposits.

CLASSIFICATION OF MINERAL DEPOSITS

All mineral deposits (*i.e.*, all aggregates of a mineral or minerals) have their original source in magmas, and thus the deposits formed by direct magmatic action are known as *primary mineral deposits*. The splitting of magmas gives rise to the *basic igneous rocks* and their accompanying group of *accessory minerals*, on the one hand, and to the *acidic igneous rocks* and a *second group of accessory minerals*, on the other. The first group of accessory minerals is the result of the first crystallization in the magma, and the second is the result of deposition from the residual mother liquors. The igneous rocks are of relatively low commercial value, but the two groups of accessory minerals produce most of our valuable ore deposits.

All primary mineral deposits may be classified according to their time relation to the rock in which they are found. Those formed at the same time as the parent rock and enclosed within it are contemporaneous or *syngenetic deposits*. Those introduced into a rock from an outside source are subsequent or *epigenetic deposits*. According to this classification, the various igneous rocks are epigenetic in that the magma itself was intruded into other rocks but are syngenetic when considered in their relationships to one another. Ore deposits of the first-formed group of accessory minerals are syngenetic, and those of the second-formed group are dominantly epigenetic.

The epigenetic magmatic ore deposits, formed as they were from the mother liquors under the widely varying conditions encountered after they passed out into the surrounding rocks, consist, naturally, of various types of deposits. These types are called *contact-metamorphic deposits*, *pegmatites*, *deposits of the deep-seated vein zone*, *deposits of the intermediate vein zone*, *deposits of the shallow vein zone*, and *surface (magmatic-spring) deposits*.

Eventually, all primary mineral deposits are subjected to alterations that give rise to new deposits, which are therefore called *secondary mineral deposits*. The secondary mineral deposits include three large groups: (1) the *sedimentary rocks*, (2) *secondarily enriched ore deposits*, and (3) *residual and detrital ore deposits*, which are formed of materials from all sources.

The secondary mineral deposits of all three groups may also be classified under the heads of syngenetic and epigenetic according to their time relation to the rock in which they are found or with which they are associated.

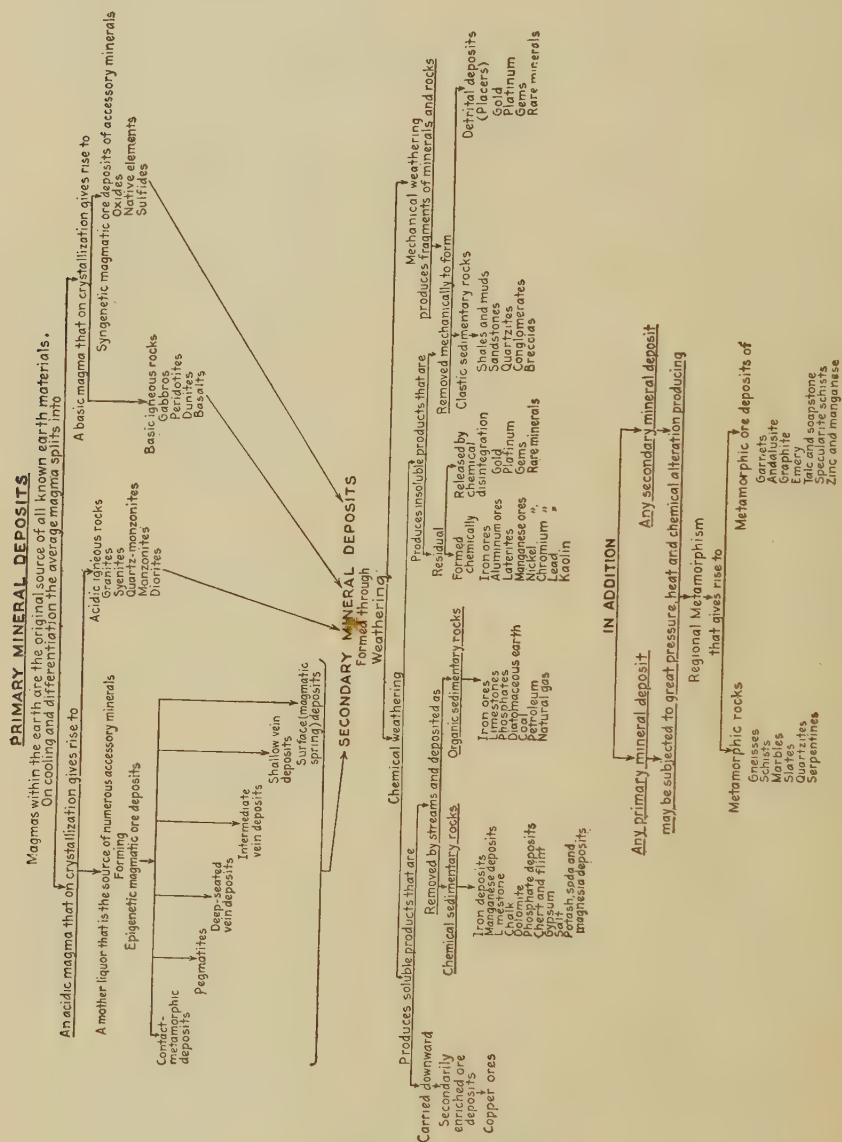


Fig. 6.—Classification of Mineral Deposits.

Finally, any primary mineral deposit and any secondary mineral deposit may be subjected to great pressure and heat which, accompanied by chemical reactions, produce *regional metamorphism*. The results of

such metamorphism are the *metamorphic rocks* and certain *metamorphic ore deposits*.

In making a classification of natural products, artificial lines must be drawn between groups or types that really grade into each other, and this should be remembered in using the classification. The value of this and similar groupings lies in the fact that they show at a glance the major relationships of the various mineral deposits. This classification is shown in more detail in Fig. 6.

PRIMARY MINERAL DEPOSITS

As seen from our classification, all mineral deposits formed by magmatic action are *primary mineral deposits*. These include *syngenetic magmatic deposits* and *epigenetic magmatic deposits*. Of the latter, there are various types according to the different conditions under which they were formed.

SYNGENETIC MAGMATIC ORE DEPOSITS

Because the syngenetic magmatic ore deposits were formed by the segregation of certain minerals within the parent rock, they are commonly called *magmatic segregations*. In general, they include those substances that are insoluble or immiscible in a silicate magma.

Minerals of Syngenetic Magmatic Ore Deposits.—Several insoluble minerals occur in minor quantities in a magma and so are found in syngenetic magmatic ore deposits. These minerals are *platinum*, *diamond*, *magnetite*, *ilmenite*, *chromite*, *hematite*, *corundum*, *spinel*, *chalcopyrite*, *pyrrhotite*, *pentlandite*, *pyrite*, and *apatite*.

The sulfides do not occur so abundantly as magmatic segregations as one might expect. The known deposits of pyrite (the most abundant of the sulfides) are relatively small in number and apparently are the result of the segregation of the small amount (5 to 6 per cent) of sulfides which a basic silicate magma can carry. Apparently, the immiscibility of sulfides with silicates has resulted in the mass of the sulfides remaining deeper in the earth's body.

Mode of Occurrence, Origin, and Form of Syngenetic Magmatic Ore Deposits.—Ordinarily, the minerals of the magmatic segregations occur in very small crystals included in or with the later minerals of the rock, in which case they are rarely in quantities large enough to be valuable, unless the mineral has an exceptional value, as has the diamond or platinum. Some magmas, however, are rich in one or two of the rare minerals; and, as solidification takes place, these minerals crystallize and are segregated by settling downward through the solution. Eventually, they form a deposit that grades into the parent rock, though some deposits may not do this, as the segregated material may have been squeezed out by earth movements into another part of the parent magma. These segregations range in form from veins to very irregular masses.

Examples of Syngenetic Magmatic Ore Deposits.—Localities where important syngenetic magmatic ore deposits are found are shown in the following table:

TABLE 6.—LOCALITIES WHERE IMPORTANT SYNGENETIC MAGMATIC ORE DEPOSITS ARE FOUND

Mineral or metal	Containing-rock	Important locality
Diamond.....	Peridotite	Kimberly, South Africa
Platinum.....	Peridotite (now in placers)	Ural Mountains, Russia
Chromite.....	Peridotite (and serpentines)	Rhodesia and New Caledonia
Ilmenite.....	Gabbro, anorthosite, norite	Norway, Quebec, New York
Magnetite.....	Syenite (probably)	Kiruna, Sweden
Corundum.....	Peridotites and gabbros (syenites rarely)	Carolinas, Ontario (syenite)
Sulfides.....	Gabbro, norite	Sudbury, Ontario; Norway

EPIGENETIC MAGMATIC ORE DEPOSITS

The epigenetic magmatic deposits were produced by all types of mother liquors, though mostly by those derived from magmas of intermediate or acidic composition. Most of the important ore deposits of the world have their source in mother liquors. The liquors vary widely in composition; from some, a pure-quartz vein will be formed; from others, a vein deposit of complex mineral aggregates.

Epigenetic magmatic ore deposits contain all the common and most of the rare minerals. The deposits have been formed under a wide range of physical and chemical conditions: from high pressures and temperatures at great depths beneath the surface to low pressures and temperatures near the surface. The deposits possess almost every conceivable shape, but veins and tabular masses predominate among them. The size of the deposits is as variable as their shape.

The formation of these epigenetic magmatic deposits involves a series of new factors that must be discussed. As the deposits were formed from the mother liquors, it will be necessary to explain the character of these liquors in order to account for their solvent power and transporting ability. And it is necessary to explain where and how deposition occurred.

CHARACTER OF THE MOTHER LIQUORS WHICH FORMED THE EPIGENETIC DEPOSITS

We know that the various gases contained in a magma accumulated in the residual liquors, because only traces of them are present in the rock-forming silicates. *Water vapor* is by far the most abundant of these gases; others are *hydrogen, oxygen, nitrogen, hydrogen sulfide, sulfur*

dioxide, carbon dioxide, carbon monoxide, hydrochloric acid, chlorine, fluorine, boron, phosphorus, sulfur, and arsenic. These gases are called *mineralizers* because they are so effective in aiding the solution and consequent transportation of the numerous other constituents of the magma. As the solutions containing the mineralizers permeate all parts of the magma, the former unite with the constituents of the magma, forming soluble compounds. As the temperature is high (above the critical temperature of water, $365^{\circ}\text{C}.$), many if not all of the compounds thus formed are present in the volatile state. Some of these volatile compounds are silicon fluoride, SiF_4 ; silicon chloride, SiCl_4 ; stannic chloride, SnCl_4 ; stannic fluoride, SnF_4 ; titanium chloride, TiCl_4 ; aluminum chloride, AlCl_3 ; aluminum fluoride, AlF_3 ; tungsten fluoride, WF_6 ; boron chloride, BCl_3 ; and ferric chloride, FeCl_3 . Most of these compounds have a critical temperature near that of water, and some, still lower; for example, tungsten fluoride boils at $19^{\circ}\text{C}.$

Objections have been made to the idea that mineral matter could be transported as a gas; but, when we recall the enormous pressure under which these gases exist (sufficient to force open the rocks about them), we can readily believe that they could move with great velocity, carrying with them their unusual volatile constituents.

It is very likely that some magmas contained insufficient quantities of halogens, or other gases, to convert all their metallic contents into volatile compounds, in which case the metals would remain in their original state until the temperature dropped low enough to permit the existence of aqueous solutions. These solutions would then be able to dissolve and concentrate the metallic content. Many ore deposits are the result of such a concentration. It is possible, also, that a concentration by this means might superimpose a second period of mineralization upon an earlier one. The conditions under which these liquid solutions exist would probably cause the formation of the colloidal form of some of the minerals. The presence of much hydrogen sulfide would tend to maintain the sulfides as colloids, and silica is believed to have been transported as a colloid from the fact that quartz veins exist where there is no quartz in the walls adjacent to the veins. A colloid could not diffuse readily through the wall rock. Gold was also probably transported as a colloid, its common occurrence in quartz veins probably being due to the inability of the gold colloid to pass through the wall rock. Alterations are produced in the wall rock by the mother liquors, however, and are called *hydrothermal alterations* because they are brought about, to a great extent, by heated solutions.

Certain it is that all magmatic solutions were mobile and, for the most part, liquid; and it is hard to conceive of a more efficient method of extracting the minute quantities of the rare substances in the magma than by the solutions during their forced progress to the inner parts of

the magma. A large magma that was rich in some one metal or group of metals (probably an isomorphous group) might give rise to deposits of great richness. One can readily believe that a huge batholith underlies southern Arizona, southwestern New Mexico, and northern Mexico and that this batholith was formerly a great copper-rich magma from which various intrusions moved toward the surface and formed the many separate copper deposits of the region.

WHERE DEPOSITION OCCURRED

For such solvents as the mother liquors, transportation is simple. All that is needed is a means of escape from the interior of the solidified magma.

Deposition in a Rock Itself.—As the liquors are gaseous and under great pressure, they can penetrate the parent rock and will do so where no easier means of escape is available. This penetration will result, of course, in the deposition of the mineral content of the liquors in grains throughout the rock. If the magma is small, the solutions might pass beyond its boundaries and deposit the mineral grains in the surrounding rocks. Rocks containing such scattered mineral grains are known as *disseminated ore deposits*. Many important disseminated deposits are known.



FIG. 7.—Filled-fissure vein.

Deposition in the Openings of a Rock.—Apparently, however, the mother liquors usually deposited their contents in openings in the rocks. The deposits thus formed are very largely of the thin, tabular type known as *veins*, although there are many variations from this type. Veins predominate because the liquors inevitably followed the major lines of weakness in the rock, *i.e.*, the joints and fissures, and deposited their mineral contents in them. These openings originated in many ways

but were primarily the result of earth movements, such as folding and faulting. Bedding planes and various other original openings in rocks are, likewise, areas where mineral deposition takes place.

Origin of Veins.—Though very wide veins occur, it is not generally believed that wide fissures existed in the rocks, especially at great depths; therefore, veins are not simply tabular cavities filled with mineral matter.

There are three prevalent views as to the mode of formation of veins. One is that the mother liquor, under great pressure, forced its way into the fissures of the rocks and held the cavities open while deposition took place. This mode of origin gives rise to *filled-fissure veins* (Fig. 7). Another

view is that *the solutions entered narrow fissures and the pressure developed as the result of the crystallization forced the walls back*. Open cavities existing in veins filled with perfect crystals, the banded structure, and other features of veins are facts opposed to this view. A third mode

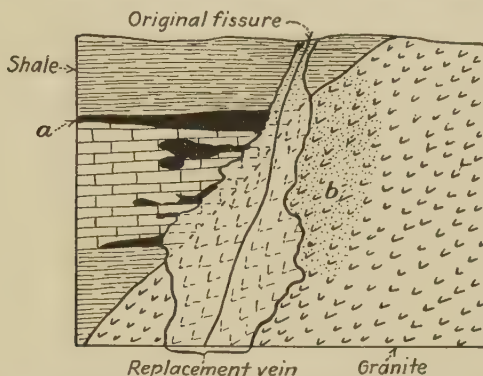


FIG. 8.—Replacement vein cutting granite and sediments. Replacement ore bodies (black areas) in limestone. *a*, bedded replacement deposit. *b*, disseminated ore body.

of origin of veins is that *the solution entered a fissure and replaced the minerals of the wall rock by the minerals it carried*. A deposit arising from this mode of origin is called a *replacement vein* (Fig. 8). The boundaries of a replacement vein are rarely as sharp and uniform as are those of the filled-fissure vein.



FIG. 9.—Ideal cross section of a lode (areas in white). *a*, horse.

Features of Veins.—Veins show a great many interesting features, only a few of which will be mentioned here.

Many veins are very large. Some are known that are 100 feet or more across and miles in length. Veins may be uniform in width, or

they may pinch out in places and then thicken again (Fig. 7). Their vertical extent is variable, some being short and others continuing to unknown depths.

Veins split into numerous branches, forming a series of parallel and diagonal veins; which, if mineralized throughout, is known as a *lode* (Fig. 9). The contents of veins are both massive and banded. The banded varieties have the minerals deposited in successive bands from the walls inward (Fig. 10). Crystals projecting into a cavity in a vein (such a cavity is commonly called a *vug*) give rise to *comb structure* (Fig. 10 b). Fragments of the country rock included in the vein are called *horses* (Fig. 9 a). Many other terms are applied to veins and to their special

features, some of which are shown in Fig. 7.

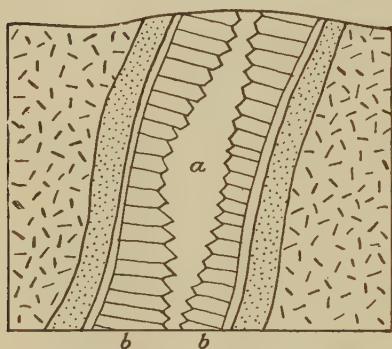


FIG. 10.—Banded vein. a, vug. b, comb structure.

Conditions Affecting the Formation of Deposits.—Filled-fissure veins are limited in extent by the walls of the opening, but replacement veins are limited only by the ability of the solution to penetrate and replace the country rock. Where deposition in a replacement vein occurs dominantly along bedded rock, a *bedded replacement deposit* is formed (Fig. 8 a). Such deposits result where the rock

replaced is surrounded by relatively insoluble rocks so that the work of the solutions is confined to a given bed. A solution may penetrate beyond the replacement zone and deposit small quantities of minerals, which form irregular disseminated deposits (Fig. 8 b) in these areas, also. Such disseminated deposits are very common, as they may form in any rock that a gaseous or liquid solution can penetrate. Rocks differ widely in their ability to be fissured and remain open. Soft rocks, such as shales, rarely contain veins, because the fractures that are formed soon close up. Hard rocks sustain well-defined fissures. Replacement deposits may form in any kind of rock, if the solution is a sufficiently strong solvent; but most replacement deposits are found in the easily replaced carbonate rocks.

CAUSES OF DEPOSITION

The materials in a mother liquor are deposited whenever the physical and chemical conditions bring about the saturation of a given substance. Pressure, heat, and the presence of various gases all influence the saturation point of a soluble constituent. Only the general character of the reactions which take place is given here. The most important factors in causing deposition are the following:

Lowering of Temperature.—Cooling a solution is a very effective means of bringing about precipitation. In fact, temperature is so important that the major divisions of epigenetic deposits are based upon its variations. The temperature of mother liquors is high (several hundred degrees); and, as it falls, those minerals that form at high temperatures will be deposited first, and so on down through the series until the solution is cold.

Pressure.—Pressure operates in two ways. Where the formation of two minerals is possible and one is denser than the other, the one having the greater density (and hence less volume) will form under conditions of great pressure. Thus, specularite, Fe_2O_3 , occurs in deep-seated veins, and hematite (also, Fe_2O_3 , but an amorphous form) at the surface. The other influence of pressure is that it causes the retention of the gases in a solution (see below).

Mingling of Solutions.—Probably one of the most important causes of precipitation is the mingling of different solutions. Differences in composition, concentration, and temperature of different mother liquors would undoubtedly bring about the formation of some insoluble compounds and consequent deposition when the different liquors mingled. Such mingling would occur where two channels leading to different magmatic sources (or the same source if the liquors had undergone different changes) crossed. Mingling of mother liquors and meteoric waters (waters from the surface) would also occur in the upper zones.

Reactions with the Minerals of the Wall Rock.—Reactions between the solutions and the minerals of the wall rock undoubtedly go on all the time; in some rocks, to a negligible degree; in others, to the extent of complete replacement. New substances are formed by the reaction of the minerals in solution with those in the wall, and the insoluble compounds formed are deposited.

Loss of Gases.—The gases present in the liquors increase the solvent power of the solutions. In many liquors, the gases are combined so loosely that they are lost by a reduction of pressure (reduction of pressure is probably common as the solutions move upward), and their loss means mineral deposition because of the reduced solvent power of the solution. The loss of carbon dioxide from calcium bicarbonate in spring waters and the consequent precipitation of calcium carbonate is an example of such a change.

Evaporation.—The direct evaporation of a magmatic solution probably never occurs; but, if it could occur, deposition would be inevitable. Evaporation is an important cause of mineral deposition at the surface.

Deposition the Result of One or More Causes.—Through any one, or, as is far more common, through the simultaneous action of two or more of the various causes of deposition, the mother liquors give rise to mineral or ore deposits.

SUMMARY

Magmatic solutions contain water vapor and numerous other gases, which become liquid when the temperature falls below their various critical temperatures. These gaseous solutions are effective solvents of most metals and rare earths, which they dissolve from the molten magma and retain as they are concentrated into the residual liquors. Most of the liquors are finally ejected from the magma and pass out into the surrounding rock, where they take advantage of lines of weakness and form larger openings in which they deposit their mineral content. The cooling of the solutions and their reactions with other solutions and with the wall rock bring about precipitation and the various resultant mineral deposits.

It is in these deposits (possibly modified later) that we find the many valuable substances, such as iron, lead, gold, copper, and tungsten, that are so indispensable in modern life.

TYPES OF EPIGENETIC MAGMATIC ORE DEPOSITS

The variable composition of mother liquors has already been emphasized. Of the thousands of granitic intrusions that have solidified in the earth's crust, it is doubtful whether the solutions given off from any two were similar. Other factors, such as temperature, pressure, and volume, also vary; so the student should not form the idea that the different types of deposits *always* grade into each other. It is much more probable that during the formation of most of the deposits, the physical and chemical conditions were suited to the formation of a single type, such as a pegmatite, a deep-seated vein, or a shallow vein. It is true that in some intensely mineralized areas there are gradations from a deposit of a deep-seated type to one of a shallower zone, but this is unusual. The mineralization following an intrusion is usually confined to *one* long or short period, during which changes in temperature and composition of the solutions are rapid or slow. Under these various conditions, distinctly different types of deposits result.

Subsequent periods of mineralization may be superimposed upon the first by solutions having their source in a deeper magma or, possibly, in a separate phase of the same magma. The correct interpretation of the primary mineralization and of subsequent changes in such a deposit requires a keen analysis of the mineral relationships, the composition of the minerals, and the changes they have undergone.

Students of mineral deposits have found that certain mineral relationships are characteristic of a given set of physical conditions and thus have been able to classify a large number of deposits in a few groups. These groups or types are given below (beginning with the deposit that is nearest to or within the parent magma):

1. Contact-metamorphic deposits.
2. Pegmatites.
3. Deposits of the deep-seated vein zone.
3. Deposits of the intermediate vein zone.
5. Deposits of the shallow vein zone.
6. Surface deposits formed by springs of magmatic origin.

The relation of these groups of deposits to the primary magma and to the surface of the earth is shown diagrammatically in Fig. 11.

Contact-metamorphic deposits are formed by the alteration of the country rock adjacent to an intrusive mass. This origin can be deduced,

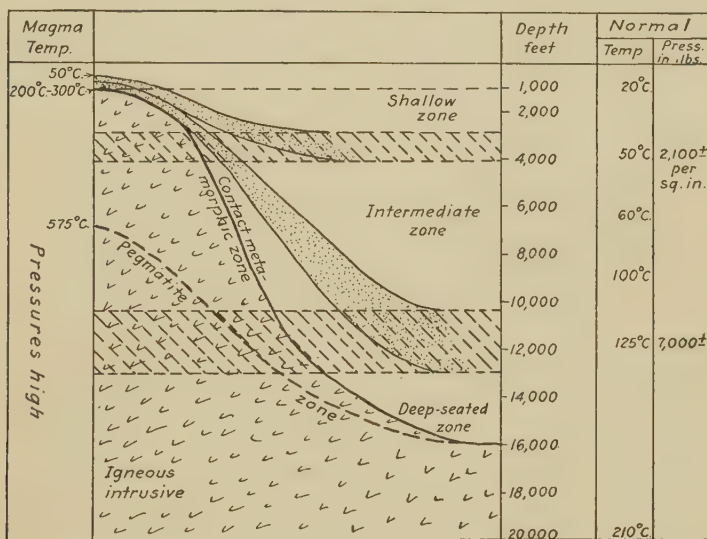


FIG. 11.—Ideal sketch of the normal mineralized zones; their estimated depths, temperatures, and pressures; and their upward deflection by a granitic intrusion. Lined areas represent overlap of adjacent zones, and stippled areas, the upward deflection of these zones. (Based on data from Lindgren, "Mineral Deposits.")

of course, from the name, which has the further advantage of being a contrasting term to regional-metamorphic deposits.

Pegmatites are regarded by some as being closely allied to magmatic segregations, and it is known, of course, that some pegmatites have crystallized within the parent magma and thus are syngenetic in origin.

The various vein deposits are formed from the mother liquors that pass outward and deposit their material in either the outer solid portion of the magma or the country rock beyond. The deposition is dominantly in the form of definite veins or lodes but may be in numerous other forms, also.

Detailed study of the genesis of the various minerals in these deposits has made it possible to subdivide them further into groups that formed under essentially the same set of conditions. This classification was

rendered difficult by the gradations of the different deposits into one another; by the repeated periods of mineralization which imposed one generation of minerals upon another; and by the presence of minerals, such as quartz and pyrite, which form under such a wide range of conditions that they may be present in all the different groups. It was possible, nevertheless, to determine that certain minerals formed normally under conditions of *high pressure and temperature* (deposits of the deep-seated zones); others, under conditions of *moderate temperature and pressure* (deposits of the intermediate zone); and still others, under conditions of *low temperature and pressure* (shallow-zone and surface deposits).

All these deposits occur dominantly in the higher parts of the batholith (usually in connection with *cupolas*, *i.e.*, protuberances on the batholith)

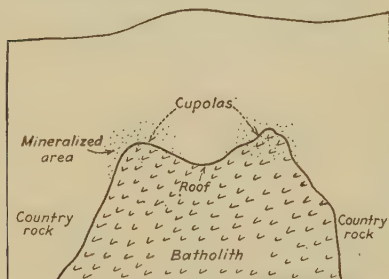


FIG. 12.—Ideal sketch of a batholith, showing roof and cupolas with mineralized area (stippled area) around them.

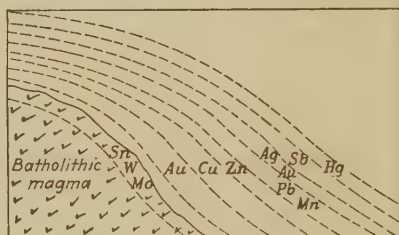


FIG. 13.—Ideal sketch of the position of the possible metallic zones extending outward from a batholithic magma. Usually, only a few of these zones are present and they are not always in sequence.

or above it (Fig. 12). This mode of occurrence is usually attributed to the ability of the gases to force their way upward, but a more important factor may have been the abundance of fractures along the zone of contact between the igneous mass and the surrounding rock. The solutions could very easily have followed this shattered zone to the high points of the batholith.

Studies of the distribution of the metals within a mineralized area have given rise to the *zonal theory*. It was found that the area surrounding a mineralizing intrusive is characterized by the presence of a certain metal or metals. The ideal sequence, beginning at the intrusive, is believed to be (1) tin, tungsten, and molybdenum; (2) gold; (3) copper; (4) zinc; (5) lead or manganese; (6) silver and gold; (7) antimony; and (8) mercury (Fig. 13). No mineralized area shows all these minerals in sequence, of course; and a number have the zones overlapping and grading into each other, producing an extremely complex aggregate of minerals that are apparently unrelated to any zone. Such deposits have

caused some doubt as to whether there is a zonal distribution of metals. The theory is logical, however, and explains the distribution of the minerals in a great many deposits. Also, it furnishes a starting point for explaining the origin of deposits whose affinities to other groups and to a magmatic source are obscure. Care must be exercised, of course, in applying it.¹

CONTACT-METAMORPHIC DEPOSITS

Contact-metamorphic deposits are formed at the contact of a magma with the surrounding rock (Fig. 14). In most of the deposits, the altera-

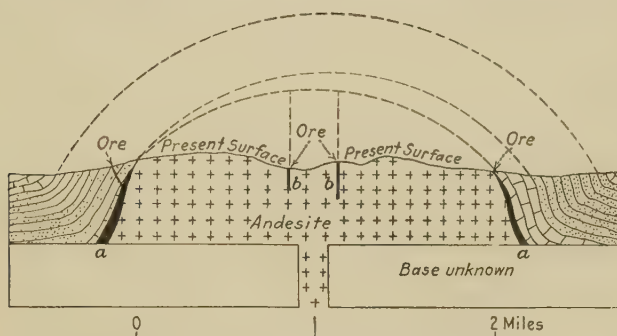


FIG. 14.—Ideal cross-section showing position of the ores as veins (b) and as contact-metamorphic deposits (a) at Iron Mountain near Iron Springs, Utah. (After Butler, U. S. Geol. Survey Prof. Paper 111.)

tion undoubtedly occurred immediately after the intrusion, while the magma as a whole was still liquid. The gases of the outer parts of the magma passed outward into the surrounding rock. The fact that the intrusive itself is unaltered up to the point of contact with the altered rock is evidence of the early formation of the contact deposits. In some contact-metamorphic deposits, however, the metamorphism occurred later, and the outer part of the intrusive is also altered. This later

¹ For further discussion of the zonal theory, see the following:

RASTALL, R. H., "The Geology of the Metalliferous Deposits," pp. 180–201, Cambridge University Press, 1923.

LINDGREN, WALDEMAR, "Mineral Deposits," pp. 136–139, McGraw-Hill Book Company, Inc., New York, 1928.

SPURR, J. E., "The Ore Magmas," McGraw-Hill Book Company, Inc., New York, 1923.

DAVISON, E. H., The Primary Zones of the Cornish Lodes, *Geol. Mag.*, vol. LVIII, pp. 505–512, 1921.

EMMONS, W. H., Primary Downward Changes in Ore Deposits, *Trans. Am. Inst. Min. and Met. Eng.*, vol. LXX, pp. 964–997, 1924.

———, Relations of Metalliferous Lode Systems to Igneous Intrusives, *Am. Inst. Min. and Met. Eng. Bull.* 1571–I, pp. 1–42, 1926.

———, Relations of Disseminated Copper Ores in Porphyry to Igneous Intrusives, *Am. Inst. Min. and Met. Eng. Bull.* 1638–I, February, 1927.

period of contact alteration was produced by the concentrated mother liquors developed in the later stages of magmatic action.

A mass as hot as a magma (variously estimated from 600 to 1,250°C.) is capable of producing important changes in the surrounding rocks if they are at all susceptible to alteration. If the temperature of the country rock is near that of the intrusive, alterations are less apt to occur. During the formation of the deposits, the temperature may range from that of the magma on down to the critical temperature of water. As a rule, granites and similar rocks are only slightly altered by intrusives. The greatest effects are produced upon limestones and dolomites and, to a lesser extent, upon calcareous shales. The depths at which the deposits form are rarely less than half a mile, and they may be as great as a mile and a half.

It is of interest to note that granitic magmas are less apt to give rise to contact-metamorphic deposits than are the slightly less acidic ones that form such rocks as monzonites, quartz monzonites, and granodiorites (see Table 5, p. 30). Basic magmas very rarely give rise to contact-metamorphic deposits.

The Minerals of the Contact-metamorphic Deposits.—The contact-metamorphic zone is characterized by the development of a group of minerals that are different from those of the other zones. These minerals are the result of reactions between materials (notably silica, iron, and alumina) of the magma and those of the country rock. The amount of material added to the altered zone varies with the temperature, the composition of the country rock and solutions, and other factors.

Silicates predominate among the minerals formed, but oxides and numerous sulfides of the common metals are present, also. Where the latter are sufficiently abundant, the deposit is of economic value. As most contact deposits are in carbonate rocks, silicates of calcium and magnesium (containing iron and aluminum from the magma) are very common.

The principal contact-metamorphic minerals are *garnet*, *epidote*, *vesuvianite*, *diopside*, *tremolite*, and *wollastonite*. *Quartz* and *calcite* are usually abundant, also. *Magnetite* and *specularite* are the chief oxides formed and may be sufficiently abundant to form valuable deposits of iron ore, as those at Iron Springs, Utah (Fig. 14). The characteristic sulfides formed are *pyrite*, *chalcopyrite*, *pyrrhotite*, *sphalerite*, and *molybdenite*. The silicates and the metallic minerals are usually intergrown.

Metals of the Contact-metamorphic Deposits.—*Copper* and *iron* are the chief metals produced from contact-metamorphic deposits. *Tungsten*, *gold*, *tin*, *zinc*, and *lead* are produced in limited quantities.

Texture of Contact-metamorphic Deposits.—The texture of contact-metamorphic deposits is extremely variable; one portion of a deposit may be dense and fine grained and another portion, coarse grained. Yet in

deposits where the alteration took place under uniform conditions, great masses may be of a very uniform texture. Openings into which well-developed crystals extend occur in various parts of a deposit. Crystals of such minerals as garnet and pyrite may be developed anywhere in easily replaceable rocks, such as limestone.

Shape and Size of Contact-metamorphic Deposits.—Contact-metamorphic deposits are extremely irregular in shape and size. They form at the side of the intrusive and spread into the adjacent country rock for variable distances (Fig. 15) but rarely beyond 2,500 feet. Slight metamorphic effects, such as recrystallization, may extend as far as a mile. The valuable portions of contact deposits may contain millions of tons of ore. A contact deposit usually grades into the country rock, but it may end abruptly.

Origin of Contact-metamorphic Deposits.—The origin of contact-metamorphic deposits is evident from their name and has already been touched upon in this discussion. One feature only remains to be described, and that is the introduction of new material into a mineral. Such an introduction involves replacement or metasomatism, which is

a very common type of alteration in rocks. In considering the introduction of new material, the question naturally arises as to what becomes of the material replaced. If none is removed, the volume of the mass would be increased. Detailed study of replacement has shown, however, that the volume of the rocks remains unchanged and that as new material is added, the old mineral is removed. The change takes place particle by particle. The intruding solution may be gaseous or liquid. The rate of replacement varies with the porosity of the rock, very dense rocks being replaced or altered with difficulty, but porous and easily soluble ones quickly. The textural details of the original rock may be preserved, or they may be entirely destroyed. The first rock may be completely replaced, or remnants of it may occur throughout the replacement deposit. At first, the alterations are rapid; but, as the solutions and temperature change, they become slower.

Examples of Contact-metamorphic Deposits.—Effects of contact metamorphism are present in a great many ore deposits associated with igneous rocks, though they have not always produced important ore deposits. Contact-metamorphic deposits occur as *copper deposits* at *Bisbee* and *Morenci-Metcalf*, Arizona; at *Bingham Cañon*, Utah; and at *Ely*, Nevada. The *iron deposits* at *Iron Springs*, Utah, and at *Corn-*

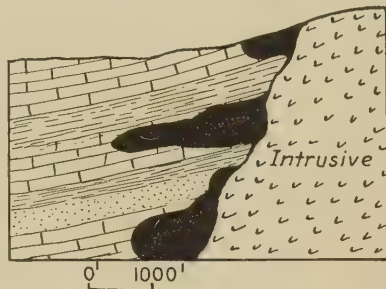


FIG. 15.—A contact-metamorphic deposit in sediments adjacent to an intrusive.

wall, *Pennsylvania*, are examples of contact metamorphism, and so are the *silver-lead-copper deposits* of the *San Francisco district, Utah*.

PEGMATITES

Pegmatites are coarsely crystalline phases of igneous rocks. They occur in association with all types of grained igneous rocks but by far the most commonly with granites. Some pegmatites contain deposits of rare elements and gems, but usually their composition is very similar to that of the rock with which they are associated.

Size of Crystals in Pegmatites.—It is the unusual size of the crystals in pegmatites that distinguishes them from their associated igneous rocks. Some of them are enormous. It is stated that a quarry in the Ural Mountains was opened in a single crystal of orthoclase. Many spodumene



FIG. 16.—Open cut of the Etta mine showing gigantic crystals (stippled area) of spodumene. The largest crystal is about 25 feet long. Black Hills, South Dakota. (After Schaller, *U. S. Geol. Survey Bull.* 610, p. 138.)

crystals in the pegmatite at the Etta Mine, Black Hills, South Dakota, are over 40 feet long and weigh several tons (Fig. 16). Beryl crystals weighing over two tons have been found in pegmatites in New Hampshire. A crystal of beryl, 18 feet long, 4 feet in diameter, and estimated to weigh 18 tons, has been reported recently at Albany, Oxford County, Maine.

The Minerals of Pegmatites.

The essential minerals in a pegmatite are the common rock-forming minerals, *feldspar*, *quartz*, *mica*, and, in the pegmatites associated with basic rocks, *hornblende* and *pyroxene*. Pegmatites usually contain, however, varying amounts of other minerals, most of which are rare and some of which are very valuable. Although many pegmatites are quarried for their feldspar, quartz, or mica; others are mined for these rare minerals, which are used as gems, mineral specimens, or sources of rare elements.

About 60 minerals are commonly found in pegmatites, and as many more occur rarely. Emmons¹ has listed the most common (not including the rock-forming minerals). His list includes 24 silicates, 14 oxides, 9 sulfides, 4 native elements, 3 phosphates, 2 carbonates, and 6 of all other groups. Some of the gems found in pegmatites are *tourmaline*, *garnet*, *beryl*, *topaz*, *spinel*, *emerald*, *sapphire*, and *aquamarine*. Pegmatites may contain a series of later-formed minerals, such as *albite*, *mus-*

¹ EMMONS, W. H., "The Principles of Economic Geology," p. 23, 1928.

covite, the lithium minerals, and garnets. These minerals are replacements of earlier ones.

Size and Shape of Pegmatites.—Pegmatites range in size from a foot to 100 feet in diameter and from a few feet to a mile in length. They vary much in shape. The thin dike or veinlike form is most common, though many outcrops are almost equidimensional in outline. Offshoots from the dikes are common.

Mode of Occurrence of Pegmatites.—Pegmatites are found chiefly in direct association with the igneous mass from which they were derived (Fig. 17). The majority occur in the outer part of the parent rock, and some extend into the rock surrounding the intrusive.

Origin of Pegmatites.—Pegmatites crystallized from the final, concentrated magmatic solutions (the mother liquors). The extraordinary size of the crystals of pegmatites is due to the great abundance in the mother liquors

of the mineralizers (water vapor, chlorine, boron, fluorine, carbon dioxide, sulfur compounds). These mineralizers, by keeping the solution very mobile, permitted the transference of material to the growing crystals for long periods of time. Elements commonly concentrated in the mother liquors are tungsten, lithium, beryllium (glucinum), columbium, tantalum, cerium, thorium, yttrium, and phosphorus.

The feldspar, quartz, and mica of pegmatites crystallized before the crystallization of the very soluble minor substances, which therefore fill the interstices between the earlier-formed minerals. These rare minerals also occur in large cavities, which are formed in pegmatites if the crystallized material is insufficient in amount completely to fill up the opening made by the original solution. Crystals of wonderful beauty are sometimes found in these cavities.

Origin of Intergrowths in Pegmatites.—A notable feature of the formation of pegmatites is the simultaneous crystallization of two minerals in approximately definite proportions, due to the fact that the solution reached the saturation point of both minerals at the same time. The results of such crystallization are remarkable intergrowths of the two minerals. The two common minerals of granite, quartz and feldspar, form most of these intergrowths in the pegmatites, and hence the resulting

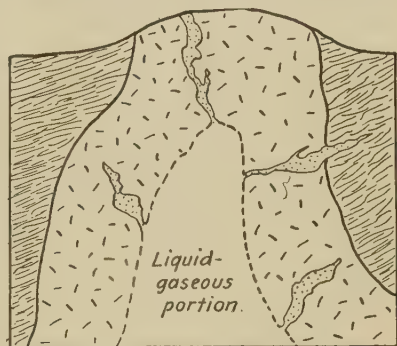


FIG. 17.—Ideal sketch of a magma showing the development of pegmatites (stippled areas).

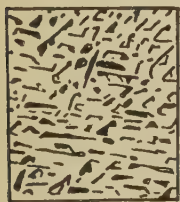


FIG. 18.—Graphic granite from Bedford, New York. Black area is quartz; white, feldspar. (After Bastin, U. S. Geol. Survey Bull. 420, pl. 3.)

rock is called *graphic granite* (Fig. 18). The intergrowths are commonly called *eutectics*, and the point of simultaneous crystallization, the *eutectic point*. There is some doubt, however, that the intergrowths of quartz and feldspar are really eutectics, because eutectics represent the final crystallization of two mineral constituents of a solution, whereas the intergrowths of many pegmatites are the result of an initial crystallization, after which the quartz and feldspar have crystallized independently of each other.

DEPOSITS OF THE DEEP-SEATED VEIN ZONE

The deep-seated vein zone contains those deposits formed at depths of 12,000 feet or more (about $2\frac{1}{2}$ miles). The temperature at which these deposits were formed ranges from the inversion point of quartz, $575^{\circ}\text{C}.$, down to $300^{\circ}\text{C}.$ At the higher temperature, gases would be abundant, but cooling would soon take place, and so, during most of the period of deposition (which, in general, is believed to be short), the solutions would be liquid.

Minerals of the Deep-seated Vein Zone.—The minerals of the deep-seated vein zone are formed under physical conditions that are somewhat similar to those under which the minerals of the contact-metamorphic zone were formed; hence, many of the same minerals occur in the two zones. In the table, worked out by Emmons,¹ showing the zonal distribution of minerals, there are 42 minerals (disregarding those of questionable distribution) common to both zones. Only 12 minerals are present in the deep-seated veins that do not occur in the contact-metamorphic zone, whereas there are 25 or more in the contact zone that are in the deep-seated vein zone.

The persistent minerals, *quartz* and *pyrite*, are abundant in the deep-seated vein zone. Other minerals present are the *feldspars*, *amphiboles*, *pyroxenes*, *garnets*, *apatite*, *tourmaline*, *micas*, *wolframite*, and *topaz*. Sulfides very commonly present are *pyrite*, *chalcopyrite*, *pyrrhotite*, *arsenopyrite*, *sphalerite*, *galena*, and *molybdenite*. Oxides are common, also, especially *specularite*, *magnetite*, *ilmenite*, *cassiterite*, and *spinel*. Gold is common. Few carbonates or sulfates occur.

Metals of the Deep-seated Vein Zone.—The deposits of the deep-seated vein zone are important sources of *gold*, *tin*, *iron*, *zinc*, *lead*, and *copper*. Minor amounts of *tungsten* and *molybdenum* are found, also.

Shape and Size of Deep-seated Vein Deposits.—Deep-seated deposits occur commonly as tabular, veinlike forms, due to the fact that the solutions producing them followed the major joints and fissures in the rocks. Where the rocks are crumpled and folded (as they are very apt to be at depths of 12,000 to 15,000 feet), the deposits are in the fractured spaces.

¹ EMMONS, W. H., A Genetic Classification of Minerals, *Econ. Geol.*, vol. III, p. 611, 1908.

Lodes are very common. Replacement has occurred along the walls of the veins, developing irregularly shaped deposits. The vein material is usually massive but it may be banded.

The size of the deep-seated deposits is extremely variable. Some are very large. The vein at the St. John del Rey gold mine in Brazil has a length of $10,000 \pm$ feet, an average thickness of 10 to 12 feet, and has been mined to a depth of more than 7,000 feet.

Mode of Occurrence of Deep-seated Deposits.—The deep-seated deposits are always associated with large intrusive masses of igneous rocks. They occur within the intrusive or in the surrounding country rock. Some deposits are closely connected and related to contact-metamorphic deposits below (may even grade into them) and to the veins of the intermediate zone above. It is believed that in some areas deep-seated deposits grade into pegmatites (Fig. 19).

Origin of Deep-seated Vein Deposits.—In forming the deep-seated deposits, the mother liquors entered the openings in the rocks under sufficient pressure either (1) to hold back the walls while deposition took place or (2) to force the solutions into the walls and thus make replacement possible. It is unlikely that the force of crystallization could have been operative in forming these deposits.

Though fault planes and other major lines of weakness in rocks offer excellent opportunities for upward movement by solutions, these openings in which the deep-seated deposits were formed were unconnected with the surface. This lack of connection was probably the cause of the formation of the lode deposits and of the wall replacements.

Examples of Deep-seated Deposits.—Deep-seated deposits are numerous and valuable. They occur as *tin deposits* in Cornwall, England, and Bolivia; and as *gold-quartz-vein deposits* in the southern Appalachian Mountains; Ontario; the Homestake mine, Black Hills, South Dakota; Mysore, India; the St. John del Rey mine in Brazil; and the Kalgoorlie district of western Australia. The *lead-silver-zinc deposits* of the Broken Hill Lode, New South Wales, Australia, and the wonderful lead-zinc deposit of the Sullivan mine, Kootenay District, British Columbia, are of this type.

DEPOSITS OF THE INTERMEDIATE VEIN ZONE

The intermediate zone of vein deposits extends from 4,000 feet below the surface to depths of 12,000 feet or more. As shown in Fig. 11

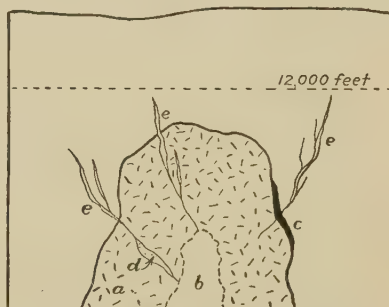


FIG. 19.—Ideal sketch of an intrusive mass within the deep-seated vein zone, showing position of various deposits. *a*, intrusive mass. *b*, liquid-gaseous core. *c*, contact-metamorphic deposit. *d*, pegmatite. *e*, deep-seated veins.

(p. 41), this zone overlaps widely with the deep-seated zone below and less widely with the shallow vein zone above. This lack of definite limits is a result of the wide range of physical and chemical factors involved. The deposits were formed under temperatures ranging from 175 to 300°C.

Minerals of the Intermediate Zone.—Some of the persistent minerals of the deeper zones are found also in the deposits of the intermediate zone; but, for the most part, a relatively new group of minerals becomes dominant. The chief metal-bearing minerals are *pyrite*, *chalcopyrite*, *arsenopyrite*, *galena*, *sphalerite*, *native gold*, *tetrahedrite* ($4\text{Cu}_2\text{S} \cdot \text{Sb}_2\text{S}_3$), and *tennantite* ($4\text{Cu}_2\text{S} \cdot \text{As}_2\text{S}_3$). There are also a number of complex minerals. The chief gangue mineral (any valueless mineral in an ore deposit) is *quartz*; but *calcite*, *dolomite*, *barite*, a little *siderite*, some *fluorite*, and a very little *albite* occur.

Metals of the Intermediate Zone.—The deposits of the intermediate zone are valuable, especially as sources of *gold*, *copper*, *lead*, *silver*, and *zinc*. Some of the largest ore deposits in the world have been formed in this zone. The deeper portions of the veins may contain *tungsten*, *molybdenum*, *bismuth*, and *arsenic*. *Antimony* is found near the top of the zone.

Shape and Size of the Intermediate-zone Deposits.—The deposits of the intermediate zone are dominantly veinlike. There are four types: (1) the *filled-fissure vein*; (2) a series of closely spaced, *parallel filled fissures* having the intervening spaces mineralized; (3) a *replacement* of the country rock adjacent to the fissure; and (4) large, irregular *disseminated deposits*. The replacement and disseminated deposits grade into each other. The former may depart widely from the tabular form, assuming very irregular shapes, especially where they occur in limestones (Fig. 20). Some of these replacement deposits are huge, cylindrical masses of minerals extending downward for unknown distances; others are lenses, usually conforming to the structure of the enclosing rocks. The solutions producing the disseminated deposits penetrated an intensely shattered rock and deposited their minerals in small grains throughout it.

The size of the deposits of the intermediate zone is variable. The veins are ordinarily thin, but they may have a vertical range of more than 4,000 feet. The disseminated deposits are of extraordinary size; some are over 2 miles long, $\frac{1}{4}$ mile wide, and 200 or 300 feet thick.

Texture of the Deposits of the Intermediate Zone.—The veins of the intermediate zone show well-defined banding and comb structure (Fig. 10, p. 38). Cavities lined with crystals (drusy cavities) are common in them. Replacement deposits may or may not show the texture and structure of the original rock; disseminated deposits do.

Mode of Occurrence of Intermediate-zone Deposits.—The deposits of the intermediate zone are genetically associated with igneous rocks

which occur as laccoliths or batholiths, usually the latter. Deposits of this zone occur in all kinds of igneous, metamorphic, and sedimentary rocks.

Origin of Intermediate-zone Deposits.—The solutions that deposited the veins of the intermediate zone are believed to have been near enough to the surface to have had some connection with it. Such a connection is

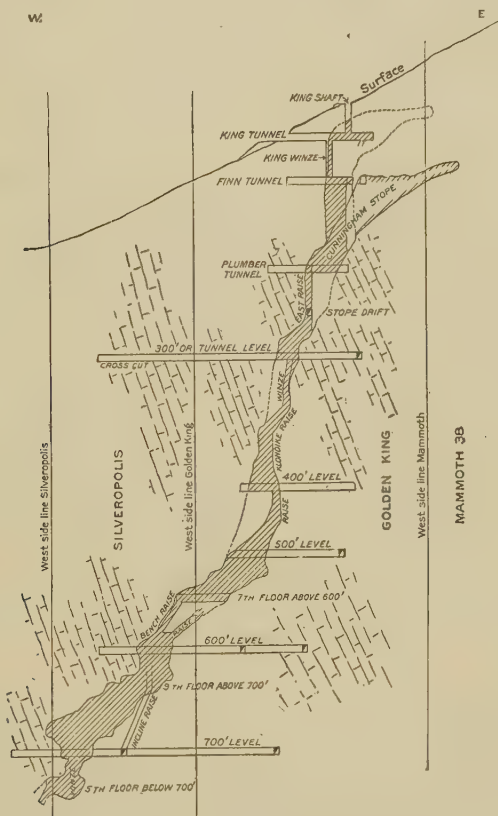


FIG. 20.—Section showing the irregular shape of a replacement ore body in limestone. Silveropolis shoot, Mammoth mine, Tintic, Utah. (Lindgren and Loughlin, *U. S. Geol. Survey Prof. Paper* 107, p. 216.)

unessential, however, as far as the formation of the deposits is concerned, for the minerals in them came from the intrusive mass with which they were connected. It is very possible that the magmatic solutions mingled with some meteoric water, in which case rapid deposition would have resulted due to the lowering of the temperature by the meteoric water. For the most part, however, the deposits were formed from the mother liquors by the normal changes in temperature and other conditions encountered as the solutions approached the upper zone.

Extensive replacement or metasomatism occurred in association with the veins of the intermediate zone. The hydrothermal alteration of the wall rock produced some very interesting minerals. These changes are known (from the chief metasomatic mineral formed) as *sericitization*, *chloritization*, *silicification*, and the like. Marked additions and subtractions of materials occurred during them. Their detailed study has thrown much light on the character of the solutions producing the change.

Example of Ore Deposits of the Intermediate Zone.—The deposits of the intermediate zone include many of the most important ore deposits of the world. Among them are the *gold-quartz veins* of *California*; the *gold deposits* of *Ballarat* and *Bendigo*, *Victoria, Australia*; the *lead-silver deposits* of *Cœur d'Alene district*, *Idaho*; the *lead veins* of *Freiberg*, *Saxony, Germany*; and the *cobalt-nickel-silver deposits* of *Cobalt, Ontario*. The *complex-sulfide deposits* of *Park City* and *Tintic, Utah*, and of *Leadville, Colorado*, are of this type, as are also the *copper deposits* of *Bingham Cañon, Utah*; *Butte, Montana*; and *Jerome, Arizona*.

DEPOSITS OF THE SHALLOW VEIN ZONE

The shallow vein deposits were formed in a zone extending from the upper limit of the intermediate veins (to which they are related) to the surface. Few were deposited below 2,000 feet, and the majority were formed within 1,500 feet of the surface. The temperature of the solutions forming the deposits was relatively low, from 50 to 200°C.

Minerals of the Shallow-zone Deposits.—A constant change in mineralogy has taken place from the high-temperature zone to the moderate- and low-temperature zones. Some of the persistent minerals continue into the shallow vein zone, but many of those present are formed only in this one.

The chief minerals of the shallow zone are *native gold*; *gold tellurides*; *argentite*, Ag_2S ; *stibnite*, Sb_2S_3 ; *cinnabar*, HgS ; *complex minerals of antimony, arsenic, silver, and copper*; *galena*; *sphalerite*; *chalcopyrite*; *pyrite*; and *marcasite*. The gangue minerals are *calcite*, *dolomite*, *rhodochrosite*, *barite*, *fluorite*, *alunite* (a potassium aluminum sulfate), and *quartz* (very commonly in the form of *chalcedony* or even *opal*). The chalcedony usually shows distinct evidence of having been deposited as a colloid. A number of rare minerals are also present in these deposits.

Metals of the Shallow-zone Deposits.—The shallow-zone veins supply a large part of the world's *silver*, all of its *mercury* (quicksilver), much of its *antimony*, and considerable *gold*, *copper*, *lead*, and *zinc*.

Many of the gold-silver deposits of the shallow vein zone have been enormously rich, forming what are generally known as *bonanzas*. The following examples have been selected from a list made by Lindgren.¹ The great Comstock lode at Virginia City, Nevada, produced in one

¹LINDGREN, WALDEMAR, "Minerals Deposits," p. 525.

month silver and gold ore valued at \$6,000,000. At Tonopah, Nevada, silver and gold ores valued at \$3,000,000 were mined in three months. The Caledonian mine at Thames, New Zealand, produced in one year \$6,000,000 worth of gold from a small ore shoot (see definition below). At Cripple Creek, Colorado, \$18,000,000 worth of gold was produced in one year from a small area, though from several mines. One of the richest bonanzas known was at Goldfield, Nevada, where a single property yielded over \$10,000,000 worth of gold in one year, and a single shipment of 47 tons in 1907 brought \$600,000. These examples illustrate the variability in richness of these shallow deposits. Unfortunately, such rich deposits are soon worked out.

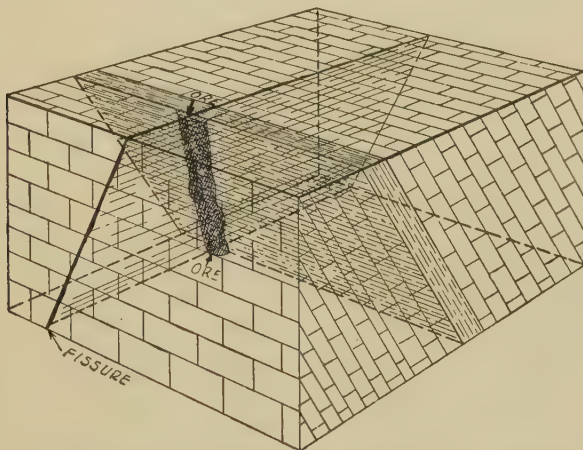


FIG. 21.—An ore shoot that has developed along a fissure in limestone beneath shale.
(Butler, *U. S. Geol. Survey Prof. Paper* 111.)

Shape and Size of Shallow-zone Deposits.—The veins of the shallow zone are typically tabular. Some veins split into numerous branches, and fragments of the wall rock may be included in them, but, on the whole, shallow veins are persistent and well defined. Some replacement occurs along the veins; and, in areas of shattered rocks, a well-defined lode may develop. The bonanzas occur in the lodes. Localized areas in the veins, which contain the richest ore, are known as *ore shoots*. These portions may be the only workable part of the deposit. The bonanzas are, of course, ore shoots (Fig. 21).

Some of the deposits of the shallow zone are of great size, *i.e.*, 200 or 300 feet across and miles in length. From these large dimensions, the sizes range down to very moderate ones.

Texture of Shallow-zone Deposits.—The shallow veins have an unusual amount of banding and very commonly contain vugs. Most of



FIG. 22.—Colloform banding of chalcidony. Specimen from the barite deposits of Washington County, Missouri.

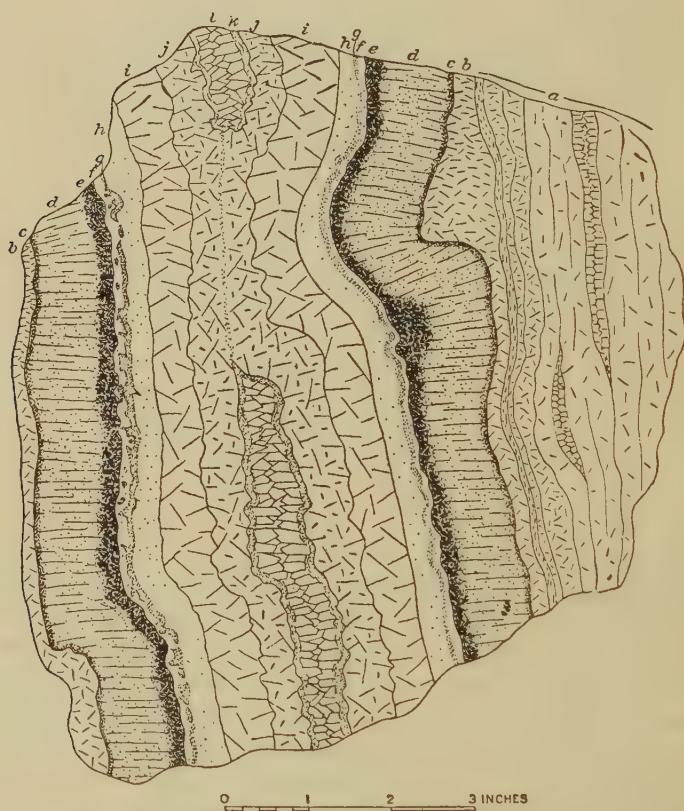


FIG. 23.—Typical banded ore from the slope above the 600-foot level of the United Eastern mine, Oatman gold district, Arizona. *a*, brown quartz in thin crusts; *b*, rather finely crystalline, white milky quartz; *c*, thin layer of honey-yellow oily-looking quartz and probably also microscopic adularia; *d*, clear quartz intimately associated with the honey-yellow variety and with calcite, probably also microscopic adularia; *e*, layer of dark calcite, quartz, and probably adularia; *f*, pale greenish-white fine-grained quartz; *g*, thin layer of honey-yellow, oily-looking quartz; *h*, like *f*; *i*, rather coarsely crystalline milk-white quartz; *k*, oily-yellow quartz; *l*, clear comb quartz. (Ransome, U. S. Geol. Survey Bull. 743, p. 35.)

the minerals of these veins are well crystallized, but some are cryptocrystalline (chalcedony) and some are amorphous (opal). The chalcedony shows typical colloform banding (Fig. 22). Banding due to the deposition of successive layers of crystals (Fig. 23) is common in these veins.

Mode of Occurrence of Shallow-vein Deposits.—More of the deposits of the shallow zone occur as well-defined veins than do those of any of the deeper zones. The veins may occur in the original igneous rock, but they are more common in the surrounding rocks. They occur in all kinds of the former but especially in intrusive porphyries and closely related types. Many of the deposits occur in sedimentary rocks. Some shallow veins have no evident connection with igneous rocks.

Origin of the Shallow-vein Deposits.—The shallow veins were evidently deposited by solutions from intrusives that were near the surface. In many mineralized areas, the solutions were apparently of unusual richness; but, whether this was due to original causes or to changes in the solutions, such as a rapid loss of their gaseous contents, is unknown.

The remarkable bonanzas were evidently the result of unusually concentrated solutions existing under conditions that were very favorable for rapid precipitation. Such conditions might arise when solutions were being rapidly cooled and, possibly, were being mixed with solutions of a different character from the surface. The presence of alunite in the sulfide ores of Goldfield, Nevada, is believed to be evidence of the mingling of meteoric and magmatic solutions. The alunite, which is a sulfate, could have originated from the mingling of a meteoric water containing oxygen with the magmatic waters which were rich in sulfides.

The veins of the shallow zone which bear no evident connection with igneous rocks are probably genetically connected with a hidden igneous mass, though as to this there is no agreement among geologists. There are good reasons for believing, however, that solutions could have readily penetrated upward from a hidden mass (cryptobatholithic mass of Emmons) and given rise to ore deposits apparently unconnected with igneous rocks, such as the lead and zinc deposits of the Mississippi Valley. Some of these are regarded as having been formed by meteoric waters, but the evidence for such an origin is unconvincing.

Examples of Ore Deposits of the Shallow Vein Zone.—A few of the important deposits of the shallow vein zone are the *gold deposits of Cripple Creek, Colorado, and Goldfield, Nevada*; the *gold-silver deposits of Tonopah and Comstock, Nevada, and the Hauraki Peninsula, New Zealand*; the *silver deposits of Pachuca and Guanajuato, Mexico*; the *mercury deposits of California, Italy, Austria, and Spain*; and, probably, the *lead deposits of southeastern Missouri and the lead-zinc deposits of Oklahoma, Kansas, and Missouri*.

SURFACE DEPOSITS FORMED BY SPRINGS OF MAGMATIC ORIGIN

It is inevitable that some of the water given off from intrusive masses should finally reach the surface and emerge as hot (or cold) springs. Magmatic waters at the surface are especially common in regions of recent volcanic activity. The numerous gas vents, or fumaroles (Fig. 24), and hot springs occurring in such regions are proofs that igneous rocks give off gases and hot waters. The hot waters of geysers are undoubtedly due to igneous masses, though not all the water of a geyser necessarily comes from this source.

Hot springs are common; but, where they have no surface connection with igneous rocks, proofs of their magmatic origin are somewhat dif-



FIG. 24.—Gases escaping from a fumarole in the floor of the crater of *la Solfatara*, an extinct volcano at Pozzuoli, Italy. (Photograph by W. A. Tarr.)

ficult to secure. Merely because a spring water is hot is not sufficient proof, for a meteoric water might penetrate deep enough to become highly heated. Many men have studied the composition of hot spring waters, hoping to obtain positive proof of their magmatic origin. Gautier's analysis of the problem is one of the best. The summary in the following table is based on his discussion:

TABLE 7.—DIFFERENCES IN COMPOSITION OF METEORIC AND MAGMATIC WATERS¹

Constituents of meteoric waters	Constituents of magmatic waters
Calcium or magnesium carbonate.....	No calcium or magnesium carbonate
Chlorides and sulfates.....	Little or no chlorides and sulfates
No sodium bicarbonate.....	Sodium bicarbonate
Little silica.....	Much silica
No heavy metals.....	Sulfides of arsenic, antimony, lead, copper, and mercury
	Gold, silver, and traces of zinc, manganese, cobalt and nickel
	Fluorides

¹ GAUTIER, A., *Compte. Rend.*, vol. CL, p. 436, 1920.

In many mining districts, hot springs occur which are depositing minor amounts of the heavy metals. At Steamboat Springs, Nevada (a few miles from the Comstock Lode district), hot springs are located along a fissure about a mile in length. Their water has a temperature of 75 to 85°C., and steam, hydrogen sulfide, carbon dioxide, and sulfur are constantly escaping from the water. The springs are depositing large amounts of silica and small amounts of the sulfides of arsenic, antimony, lead, copper, and mercury; the iron oxides; gold; silver; and traces of other metals. Springs of magmatic origin at Wagon Wheel Gap, Mineral County, Colorado, are depositing gold and silver, an abundance of fluorite and barite, and traces of other metals. The hot springs at Ojo Caliente, Taos County, New Mexico, deposit a calcareous tufa which contains small amounts of fluorite, some limonite, and traces of gold and silver. Some of the springs in Norris Geyser Basin, Yellowstone Park, are depositing arsenic sulfide. The hot springs of Hot Springs, Arkansas, which are believed by some men to be of magmatic origin, contain only 279 parts of mineral matter per million, of which 164 parts, or 58.7 per cent, is the bicarbonate radical; 47 parts, or 16.7 per cent, silica; 46 parts, or 16.3 per cent, calcium; and the remainder, composed of minor constituents. Numerous other examples could be given, but these are sufficient to show that waters of magmatic origin do reach the surface and form deposits.

None of these spring deposits is of economic value, but they are all of interest in completing the sequence of events which take place as a solution passes outward and upward from a magmatic mass.

Magmatic solutions have probably reached the surface beneath the sea and contributed their materials to the sea water or possibly deposited them on the sea floor. Some men believe that the great iron deposits of the Lake Superior region originated in this way.

SUMMARY

This discussion began with the source of a magma within the earth and followed the magma through a series of changes that produced the igneous rocks, on the one hand, and a residual mother liquor, on the other. This splitting was brought about by the crystallization of the silicates of the magma as the rock-forming minerals and, at the same time, the segregation of the mother liquors within the parent rock. Most of these residual solutions eventually passed outward and, because of their physical and chemical character, were able to carry with them many rare substances which were deposited wherever conditions were favorable. As a result, contact-metamorphic deposits, pegmatites, and the veins of the different zones were formed. Each type of deposit has certain distinctive characteristics.

The mineral deposits formed as a result of magmatic action are the primary source of all materials now at the earth's surface (for, by our definition, mineral deposits include all earth materials). In spite of the numerous gradations that exist between the different types of primary deposits, a complete sequence from those that crystallized within the magma to those formed at the surface by springs of magmatic origin does not exist. This merely means that a particular set of heat, pressure, and chemical factors will produce one type of deposit and that another set of factors will produce a different type.

Some of the primary mineral deposits constitute the chief source of many valuable metals and other substances used by man; hence, are ore deposits. The world-wide association of ore deposits with igneous rocks leaves no doubt as to the genetic association of the two, and the above-outlined, logical sequence of events points to the same conclusion.

SECONDARY MINERAL DEPOSITS

According to our definition, all aggregates of minerals are mineral deposits, irrespective of their origin. The previous discussion has shown that all the types of deposits produced from a magma are primary mineral deposits. All other deposits, then, must have been derived from these primary deposits and are *secondary mineral deposits*. The secondary mineral deposits include (1) *the sedimentary rocks*, (2) *secondarily enriched ore deposits*, and (3) *residual and detrital ore deposits* (Fig. 6, p. 32).

As in the production of the primary deposits, solutions are essential in producing the secondary deposits, and, again also, water is the chief agent. Gases are somewhat effective in producing secondary deposits, especially the common gases of the atmosphere. There are marked differences in the composition of magmatic and meteoric solutions, but each is effective in its own sphere. Secondary mineral deposits are produced by the processes of weathering, which operate at or near the surface.

WEATHERING

Weathering is the alteration produced in mineral deposits (rocks and ore deposits) by *mechanical* and *chemical* means. *Changes in temperature* produce the chief mechanical effects, and the erosive agents, *water* and *the atmosphere*, are the chief chemical agents. The constant attack of these upon a rock eventually changes it into another type.

Essential Factors in Weathering.—The constant alterations going on in rocks are due to the law of stability of minerals. A mineral is stable as long as it remains in the physical and chemical environment in which it was formed. If it is moved elsewhere, it becomes susceptible to alteration, unless it belongs to the class of persistent minerals which are durable under a wide range of conditions. Quartz is such a mineral, forming under high-temperature conditions and yet strongly resisting

weathering when it has been moved to the surface. Feldspar, on the other hand, undergoes complete alteration to other substances when moved out of its original environment, as happens when, by long-continued erosion, a granite is exposed at the surface. The character of the new material formed when the original material breaks down depends upon the conditions under which the change is produced. *The change will always produce a mineral that is stable under the existing physical and chemical conditions*, however. Thus, kaolin is formed from the feldspar because kaolin is more stable at the surface than feldspar. It is not surprising, then, that shales and clays, which consist dominantly of kaolin or closely related minerals, constitute 80 per cent of all sedimentary rocks. The weathering of the numerous iron-bearing silicates of the igneous rocks, also, furnishes evidence of the law of stability, for the iron of the silicates becomes the more stable (at the surface) iron oxide.

Agents of Weathering.—As already mentioned, the process of weathering is of both a *mechanical* and a *chemical* nature. The agents of mechanical weathering are *temperature changes*, *abrasion*, and *corrasion*. The agents of chemical weathering are *water*; the common gases, *oxygen* and *carbon dioxide*; and minor amounts of certain gases formed by chemical reactions.

MECHANICAL WEATHERING

The mechanical breaking up of a rock is largely due to changes in temperature, which cause an alternate expansion and contraction of its particles. This action slowly but surely causes disruption. When the temperature drops below freezing, the expansion of the ice formed from any moisture present in the rock is a further aid in disintegration. The growth of roots in cracks of rocks aids in breaking up the rock. The mechanical wear (abrasion) of rocks by wind, water, and ice produces much fine material upon which solutions can act.

CHEMICAL WEATHERING

The Presence and Effects of Water.—Water, at least in small quantities, is present everywhere. The atmosphere contains varying amounts of water vapor; and water is present on the surface of the earth, in the soils, and in the rocks beneath. Pure water will attack and dissolve a great many substances, usually very slowly, to be sure, but the process is going on continuously in the rocks and, in the end, produces considerable changes. Water containing the weak carbonic acid is a better solvent, and water containing a strong acid, such as sulfuric, is a very effective one. The common radicals of the average meteoric water are CO_3 , SO_4 , and Cl . Only under rare circumstances are others present. As a result, the soluble substances carried by surface waters are mainly carbonates, sulfates, and chlorides. Smaller amounts of colloidal silica and the more difficultly soluble substances are present.

The Presence and Effects of Gases.—Oxygen and carbon dioxide are present, not only in the atmosphere but also dissolved in all meteoric waters. They are liberated by organisms; and an additional source of carbon dioxide is the combustion of coal, oil, wood, and gas. Both of these gases take part in numerous chemical reactions involved in weathering.

Temperature of Meteoric Waters.—Meteoric waters are dominantly cold solutions. Essentially all their work is accomplished at the temperatures prevailing at the surface. The temperature of the earth increases downward, but few meteoric waters attain depths that would raise it more than a few degrees. Meteoric waters may become heated by coming in contact with hot igneous rocks, but such occurrences are so rare as to be unimportant in the general process of weathering.

Zone of Chemical Weathering.—The water on the immediate surface accomplishes some chemical work, but most of the chemical weathering is accomplished beneath the surface, where the solutions follow the openings in the rocks or make new ones.

Openings in Rocks.—A great deal has been written about the openings in rocks, but only the general features can be considered here. Ordinarily, these openings are divided into two classes: *primary openings*, which were formed at the same time as the rocks, and *secondary openings*, which were formed subsequently.

Examples of *primary openings* in rocks are the pore space of sandstones, gravels, breccias, and volcanic tuffs; the space between the minerals particles of all rocks; the space along bedding planes in rocks; the openings due to gas bubbles in lavas; and the cavities in veins. A solution can move through these openings if they are large enough and connected. If they are unconnected but are large enough to permit the entrance of solutions, they are still available as space where deposition may take place.

Secondary openings in rocks are those of joints and fissures developed during cooling (of igneous rocks); consolidation (of sedimentary rocks); and by earth movements, such as folding and faulting. These openings lie at all angles to the surface and are of all sizes. Some are persistent for miles; others are invisible. All joints disappear at the zone of flowage, which begins at a depth of about 11 miles below the surface.

Openings in rocks have been assigned the following arbitrary sizes:

	For round openings, millimeters	For sheet openings, millimeters
Supercapillary openings—greater than.....	0.508	0.254
Capillary openings—between.....	0.508 and 0.0002	0.254 and 0.0001
Subcapillary openings—less than.....	0.0002	0.0001

The active circulation of ground water takes place in the supercapillary openings. The laws of capillarity operate in the capillary openings, where, of course, no active circulation takes place. There is no movement of any kind in the subcapillary spaces; any moisture present in them is simply retained. The laws of hydraulics apply only in the supercapillary openings.

Depth to Which Water Penetrates.—Meteoric water, working its way down through the openings in the rocks, conceivably might go as far as the openings extend, *i.e.*, about 11 miles. On account of the temperature increase downward, however, it would be converted into a gas before it reached that depth. A rate of temperature increase of 1°C . for 100 feet would give a temperature of 100°C . at 9,000 feet, but the temperatures observed in recent drill holes to this depth indicate that the above rate of increase is too high. The evaporation point of meteoric waters would certainly be reached at a depth of less than 3 miles. (This leaves out of consideration, of course, the abnormal rise of temperature due to the presence of an intrusive magma.)

We have, however, much more important evidence than the above theoretical considerations that meteoric waters do not extend to great depths. The fact that deep mines are dry and dusty and that water has to be piped down for use by the workers is direct and incontestable evidence. Where the rocks in mines are strongly fractured and jointed, water exists to depths of about 4,000 feet, but the great majority of mines are dry below 1,000 or 1,500 feet. This shows that surface waters do not normally penetrate below a thin zone at the top of the earth's crust. In drilling essentially all deep oil wells, water must be pumped into the holes for drilling purposes. Some deeply buried sandstones contain water, but this was in the rock materials when they were laid down and was thus buried with them.

Water Level.—The term "water level" or "water table" is used so frequently that it needs consideration. The water level of an area is the top of the zone that is saturated with water (Fig. 25). This upper surface roughly follows the topography of the area, but the character of the rocks may cause great variations in this. In some areas, the water level is a few feet below the surface, and thus water is easily reached by shallow wells; in others, especially arid regions, wells may have to be 1,000 feet or more deep, or perhaps no water can be found. It has been

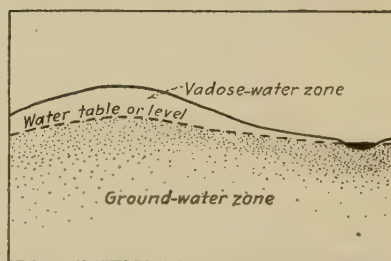


FIG. 25.—Diagrammatic sketch of the vadose-water zone; water level or water table; and ground-water zone. The degree of saturation is indicated by the density of the stippling.

estimated that the total amount of ground water would form a layer about 96 feet thick over the entire surface of the earth.

The zone of active circulation and, thus, of effective chemical work of underground water lies above the water level. The water in this zone is known as "vadose water" (Fig. 25). Below the water level, chemical changes may go on slowly by diffusion through the quiescent ground waters.

Rate of Movement of Underground Water.—The rate of movement of underground water in the zone of active circulation varies with the size of the openings and the volume of water, and these two factors are so variable that only estimates of the rate of movement can be made. In some rocks, the rate would be measured in feet per minute; in others, feet per hour; and in still others, inches per day.

CHARACTER OF THE CHANGES IN CHEMICAL WEATHERING

The character of the changes which take place during chemical weathering are comparatively simple. These involve *oxidation*, *carbonation*, *hydration*, and a certain amount of *exchange of materials*.

The normal meteoric water passing through the rocks is a carbonate solution, though the carbon dioxide plays a very small part in breaking up the aluminous silicates. The reaction is primarily one of *hydrolysis*, as shown by the following equation:



During the chemical weathering of igneous rocks, the silica of the silicate minerals either enters new silicates, such as kaolin and serpentine, or is set free as colloidal silica; the iron becomes the iron oxides; calcium, magnesium, and sodium readily form carbonates (or sulfates); and the potash is largely absorbed by the kaolin and colloidal silica formed. Only a small amount of potash is carried out in solution as the carbonate or sulfate.

Thus, we see that the new minerals commonly formed by chemical weathering are *carbonates*, *sulfates*, *oxides*, and *silicates*. Most of these are hydrous. Considerable material is removed in solution, for carbonates, sulfates, and colloidal silica are relatively soluble.

The ever present calcium of the igneous rocks has a strong affinity for the CO_2 radical, found so abundantly in meteoric waters, and so calcium always forms CaCO_3 under surface conditions. Calcium carbonate is, however, relatively soluble in the presence of carbon dioxide; therefore, beds of limestone readily pass back into solution; again become solid; and so on around the cycle. The law governing the formation of a new mineral is that it shall be stable in the environment in which it is developed, and calcium carbonate is the form in which calcium must

exist at the surface, whether in a soluble or a solid state. This is equally true for other products, such as gypsum and salt.

The nature of the normal meteoric solutions and of the resultant secondary mineral deposit is affected, of course, by special factors. The presence of unusual minerals in the rock being weathered will mean a solution of unusual character and secondary minerals that depart from the normal order. Thus, an unusual amount of pyrite in a granite would mean an abundance of the sulfate radical and might mean free sulfuric acid. A solution resulting from the weathering of such a rock would be capable of producing profound changes. Many primary sulfide deposits are changed into more valuable deposits as a result of such weathering.

Though the composition of the original rock greatly influences the character of the intermediate minerals formed during chemical weathering, it has little effect on the end products of chemical weathering. Where chemical weathering is the dominant process going on, these *end products are the hydrous and anhydrous oxides of aluminum, iron, and titanium*. These are the most stable and insoluble minerals produced at the surface, and they are formed from the chemical weathering of all kinds of primary mineral deposits. If chemical weathering alone could be operative, the surface of the earth would be covered by a layer of these insoluble oxides. Their formation, however, calls for such a delicate balance of so many fundamental geologic processes that they develop only in very local areas.

PRODUCTS OF WEATHERING

The materials resulting from the chemical decomposition and the mechanical disintegration of the primary mineral deposits are the substances from which the secondary mineral deposits are formed. The materials produced by weathering will be discussed under the following heads: (1) *fragmental materials* (produced by both mechanical and chemical weathering and giving rise to the clastic sedimentary rocks and placers of heavy minerals); (2) *residual insoluble materials* (produced by chemical weathering and giving rise to deposits of very insoluble ore minerals); (3) *soluble materials removed by streams* (produced by chemical weathering and giving rise to chemical and organic sedimentary rocks and ore deposits); and (4) *soluble materials carried downward* (produced by chemical weathering and giving rise to secondarily enriched ore deposits).

FRAGMENTAL OR DETRITAL PRODUCTS OF WEATHERING

The fragmental materials produced by weathering include not only all the materials produced by mechanical weathering but also the clay

particles *formed* (and carried away) and the insoluble minerals *released* during chemical weathering.

The Clastic Sedimentary Rocks.—Most of the material produced by the mechanical weathering of a primary mineral deposit consists of fragments of *quartz*, *feldspar*, and *mica*; and these fragments, together with the *clay* particles produced chemically, make up the *mantle rock*. Eventually, the fragments are carried away by streams, sorted, and deposited as the various *clastic sedimentary rocks*. These, where suitable, are used economically as gravel, sand, and clay. The unsorted material of the mantle rock is of little economic importance, except as the material from which soil is formed.

Ore Deposits of Insoluble Heavy Minerals.—Hard, heavy, insoluble minerals (such as gold, platinum, and various gems and rare minerals) occurring in the primary rock are released chemically by the solution of the other constituents of the rock and mechanically by the usual mechanical means of rock disintegration. By whichever method these minerals are released, they may be later concentrated by running water, wind, or waves into *detrital ore deposits* or *placers*. A stream forms a placer deposit in its channel, and waves rework the fragmental materials and concentrate the heavy minerals on the shore. The wind forms a placer deposit above the original rock (it would thus be a residual deposit, also) by removing the finer and lighter materials from among the heavy minerals.

Concentrates of heavy minerals are seldom formed far from the original source of the minerals. The concentrates or placers are associated with gravels and sands. Because of their greater weight, the ore minerals occur at the very bottom of the deposits.

Placers are the world's chief source of *platinum*, and they furnish a large part of its *gold*, *tin*, and *gems*. The diamond deposits of Brazil, the gold deposits of the Rand district in South Africa, and various deposits of iron ores can probably be classified as placers.

RESIDUAL PRODUCTS OF WEATHERING

While the silicates and other minerals of the primary mineral deposit are being broken up during chemical weathering, insoluble compounds are formed. These compounds are *silicates*, *oxides*, *sulfates*, and rarely *phosphates*. The most abundant mineral formed during this chemical disintegration is the silicate mineral *kaolin*, which is made by the breaking up of feldspar and other aluminous minerals. Most of this kaolin, as we have already seen, is removed as fragmentary clay particles and gives rise to the clastic sediment shale. Some of it, however, is not removed, and so residual deposits of kaolin or clay are formed.

The chief *ore minerals* of residual deposits, however, are the *oxides* (more or less *hydrous*) of *iron*, *manganese*, *aluminum*, and *chromium*; *nickel silicate*; and *lead sulfide*.

Iron Oxides.—Whatever may be the form of the iron in the original rock, it eventually becomes the ferric oxide in the weathered material. (Under certain conditions, noted later, iron is soluble.) The two common iron oxides, hematite and limonite, are very insoluble (more insoluble than quartz); hence, they accumulate as quickly as they are formed and, unless removed mechanically, give rise to a deposit of iron ore. The deposit may rest upon the surface of the source rock, or it may occur in residual clay which was formed at the same time as the oxides (Fig. 26). Large and valuable deposits of iron have been formed in this way.

Manganese Oxides.—The manganese of a primary deposit undergoes an oxidation similar to that of iron, but deposits of manganese oxide are



FIG. 26.—Diagrammatic sketch of a primary igneous rock (A); altering to clay (B); iron ore (black dots); a bed of residual iron ore (solid black) above; and isolated masses of ore in the clay down the slope.

less common because manganese is not so abundant. As it is slightly more soluble than iron, it may, during weathering, be carried farther from the original source before being deposited.

Aluminum Oxides.—The aluminum of the aluminous silicates normally enters into the composition of kaolin. Kaolin, however, under topographic conditions that permit its long-continued leaching by meteoric waters rather than its removal, is eventually broken up. The silica of the kaolin is removed, and the very insoluble hydrous aluminum oxide (bauxite) remains. Bauxite is the chief source of aluminum.

Chromium Oxide.—Chromite, $\text{FeO} \cdot \text{Cr}_2\text{O}_3$, is insoluble and thus is concentrated at the surface, as the original rock containing it (usually a magnesian rock) is removed.

Laterites.—Laterites are residual deposits of the oxides of iron, aluminum, titanium, and silicon; all are more or less hydrous. The amount of iron may be high enough to form a fair-grade iron ore, and some laterites contain aluminum as the most abundant constituent. Titanium and silicon oxides are usually present in small amounts. Laterites may form over any type of rock by long-continued chemical weathering.

Nickel Silicates.—The small amounts of nickel present in such rocks as peridotites replace part of the magnesium in secondary magnesium

THE CHEMICAL SEDIMENTS

Two groups of chemical deposits are formed. One consists of those substances that are *relatively insoluble in sea water* or saline lakes and thus are rapidly precipitated. Such substances are *calcium carbonate*, *iron compounds*, *phosphates*, and *colloidal silica*. The other group consists of substances which are so *soluble in salt waters* that they must accumulate in large quantities before they are precipitated. This group includes *calcium sulfate*, *sodium chloride*, and *potassium and magnesium compounds*.

Deposits of Relatively Insoluble Minerals.—The materials which are relatively insoluble in salt water are, consequently, soon deposited. These can be likened to the minor substances of a magma that crystallize out in the early stages.

The Most Common Chemical Deposits.—The principal substances carried to the sea are, in the order of their abundance, *calcium carbonate*, *silica*, and *magnesium carbonate*. Some idea of the amounts carried annually may be gained from Clarke's calculations, given in the following table:

TABLE 8.—THE AMOUNTS OF CALCIUM, SILICA, AND MAGNESIUM CARRIED ANNUALLY TO THE SEA BY RIVERS¹

Substance	Amount, metric tons
Calcium, Ca.....	557,670,000
Silica, SiO ₂	319,170,000
Magnesium, Mg.....	93,264,000

CLARKE, F. W., Data of Geochemistry, U. S. Geol. Survey Bull. 770, p. 138.

Analyses of sea water show that practically no calcium or magnesium carbonate or silica is present in the sea, which indicates that the large amounts constantly being added by the rivers must be precipitated at once. Some calcium and magnesium form chlorides and sulfates in the sea water, but the amount of such salts would account for only a very small percentage of the large amounts of calcium and magnesium brought in by the rivers.

The *calcium* that goes to the sea is deposited almost entirely as the carbonate, only a small amount being precipitated as the sulfate (gypsum). Some calcium carbonate is used by organisms for their hard parts; some is precipitated. Under special conditions, this precipitation is aided by bacteria, but it can go on without their participation, because calcium carbonate soon reaches its saturation point in sea water. The accumulation of the precipitated calcium carbonate on the sea bottom forms beds of *limestone* and *chalk*. The author of this volume¹ regards chalk as being, dominantly, a chemical precipitate.

¹ TARR, W. A., Is the Chalk a Chemical Deposit? *Geol. Mag.*, vol. LXII, pp. 252-264, 1925.

The *magnesium* added to the sea water is largely precipitated as the carbonate, but a portion remains in solution as the sulfate and chloride. The precipitated magnesium carbonate is usually in the form of the double salt $\text{CaCO}_3 \cdot \text{MgCO}_3$ (dolomite). The simple magnesium carbonate MgCO_3 (magnesite) may, however, be deposited, also. Magnesium carbonate is more soluble than calcium carbonate, so the latter will be precipitated from a less concentrated solution than the former. The double carbonate was probably precipitated in the more concentrated waters of epicontinental seas. The common occurrence of dolomite with saline deposits of salt and gypsum indicates that this was true. Chemically precipitated magnesite is of rare occurrence.

All the *silica* added to the sea is soon precipitated. A part, in the form of the colloid, goes down with the clays; a smaller part is used by siliceous organisms in the sea; a small portion is used in the formation of glauconite (which makes use, also, of some iron and potash); and the remainder is precipitated directly upon the sea floor as a colloidal mass that, upon losing its water, becomes *chert* and *flint*.¹ Chert and flint form beds and lenses but occur, also, as nodules within limestone and dolomite. They are found in enormous quantities in the beds of certain geological periods, notably the Ordovician, Mississippian, Pennsylvanian, and Cretaceous.

Rare Chemical Deposits.—Deposits of chemically precipitated *iron*, *phosphorus*, and *manganese* minerals are formed but in much lesser abundance than those of calcium and magnesium carbonate and silica. They are very valuable, however, forming as they do the world's chief source of these minerals.

The greatest deposits of *iron* in the world are of sedimentary origin. Magmatic deposits occur, but they are relatively unimportant in amount. The iron of the sedimentary deposits may have been *brought to the sea* in two different ways. As the ferrous carbonate, it may have been *carried by rivers* and deposited in any of the following ways: (1) by precipitation as the carbonate; (2) by oxidation (probably aided by bacteria) of the ferrous salt to ferric oxide; (3) by the replacement of fossils and oolites by ferric oxide; and (4) by deposition as the silicate. Valuable and widespread deposits of iron originate in this manner. The other way in which the iron may have been *brought to the sea* is in *magmatic solutions* which enter from below, precipitating the element as the carbonate or silicate on the sea floor. Some men believe that the iron ores of the Lake Superior region originated from magmatic waters on the sea floor, and others that they were brought in by rivers after being obtained during the weathering of surface rocks.

Nearly all important *phosphate* deposits were formed chemically, though, in all, organisms played some part in concentrating the materials.

¹ TARR, W. A., The Origin of Chert and Flint, Univ. Missouri Studies, vol. I, 1926.

In most deposits (especially in the large deposits of western United States), the final deposition was through chemical means. Phosphate deposits, as well as deposits of many other minerals, illustrate how more than one agency plays a part in the formation of a mineral deposit.

Manganese deposits are formed by the same methods as deposits of iron; and, even though manganese is much less abundant than iron, there have been times when it was so plentiful that it was carried to the sea and deposited, usually as the oxide. The deposits are very rarely rich enough to mine, yet the great manganese deposits in Kutais Province, Georgia, just east of the Black Sea, are of this type.

Deposits of Very Soluble Salts Formed by Evaporation.—The group of very soluble compounds carried to the sea is deposited, finally, by evaporation of the sea water.

The saturation point of *calcium sulfate* is first reached after evaporation of the water begins, and *gypsum* is thus precipitated, forming a bed over the floor of the body of water. *Salt*, NaCl, is the next mineral to be deposited; and then, after the solution is nearly all evaporated, the extremely soluble *salts of potassium and magnesium* are laid down. The world's supply of these minerals comes from such deposits, which have been formed at different times during the earth's history and in widely scattered regions.

A group of *sodium compounds*: carbonates, sulfates, borates, and nitrates, is formed by local concentration in inland lakes, especially in arid regions. Some of these deposits are very important as sources of rare materials, such as the nitrates.

THE ORGANIC SEDIMENTS

Organisms utilize various inorganic materials in their life processes; and, after the death of the organisms, the accumulations of these segregated materials give rise to various mineral deposits. These deposits are of three kinds: *calcareous*, *siliceous*, and *carbonaceous*.

Organic Calcareous Deposits.—Most of the shelled organisms in the sea use calcium carbonate for their hard parts. Where the organisms are very abundant, thick beds of shells accumulate after their death. Consolidation of these remains gives rise to beds of limestone.

Organic Siliceous Deposits.—Several types of organisms living in the sea make use of silica for building their hard parts. Some of these organisms are plants, as the diatoms; others are animals, as the sponges. Only the diatoms, however, have given rise to siliceous deposits of a size sufficient to be of economic importance. Diatoms have lived formerly in enormous numbers in sea waters rich in silica, and consequently beds of *diatomaceous earth* hundreds of feet in thickness have accumulated in various localities over the earth.

Organic Carbonaceous Deposits.—In the formation of organic carbonaceous deposits, a new factor is involved, that of the contribution of the atmosphere. Oxygen, much carbon dioxide, and water have their source in the air; and, just as gases play a part in magmatic action, so these gases of the atmosphere contribute to the formation of mineral deposits, but through organic agents. The organisms are dominantly plants, though animals probably contributed considerable material to the formation of petroleum. The organisms obtain the carbon largely from the air. Water is very necessary to the formation of carbonaceous deposits, though it contributes little of the source material. Where the remains of organisms accumulate in water, however, they are preserved instead of becoming decomposed. Subsequent changes convert the material into *coal*, *petroleum*, and *natural gas*. The sequence of events necessary to the formation of these three materials is not the same, nor does it take place under the same conditions.

That man is directly dependent upon organisms, long dead, for more than one-half of the total value of earth materials he uses is probably not realized by many, but such is the case.

SOLUBLE PRODUCTS CARRIED DOWNWARD

It has already been pointed out that although the larger part of the soluble products formed by weathering are carried away by streams, a part finds its way downward into the underlying rocks. However, though meteoric waters work their way downward into the rocks everywhere, they do not, for the most part, bring about the formation of important mineral deposits.¹ They do accomplish a large amount of geological work, but it is principally solvent work. New minerals are formed by means of meteoric water, but they usually become a part of the soil. Considering the large amount of water that reaches the water level, it is surprising that so little mineral matter is carried downward. Considerable cementation does go on locally, but in view of the important changes that take place at the surface, the small amounts of depositional work going on below the mantle rock is one of the striking and unexpected facts concerning underground waters. In local areas, which are infinitesimal when compared with the total surface of the earth, important changes have taken place, and our discussion will, of course, have to do with the results of these unusual alterations.

Theories of the Origin of Mineral Deposits.—There has been much discussion about the possible methods of formation of valuable mineral deposits by meteoric waters. Sandberger, in 1880, presented the results

¹ CLARKE, F. W., Data of Geochemistry, U. S. Geol. Survey Bull. 770, p. 648. Clarke's discussion on this and succeeding pages is of much interest and value in connection with the formation of ore deposits.

of several years' labor. He sought to show that all mineral deposits had resulted by meteoric waters' having dissolved the metals from the rocks and deposited them in veins. For 20 years, this view was widely accepted, although often with modifications. About 1900, a valuable series of papers by Kemp, Lindgren, and others appeared that developed the theory of a magmatic origin for ore deposits. Many objected to this view, but its supporters grew in number in spite of Van Hise's lengthy monograph upholding a meteoric origin. A magmatic origin (as developed by the above-mentioned pioneers and their supporters) for the majority of all primary mineral deposits is generally accepted today. The genetic relationships of some deposits are still obscure, however; and so, a controversy as to their origin still exists. In spite of the overwhelming amount of evidence against the ability of meteoric waters to accomplish the concentration needed for the formation of such deposits as those of zinc and lead in Oklahoma, Kansas, and Missouri, such an origin is advocated by some men for these deposits. In the following discussion, it will be shown that certain mineral deposits have undergone important secondary changes due to meteoric waters but that others, about which there is still dispute, are better explained by a magmatic origin.

Objections to the View that Meteoric Waters Are the Source of Ore Deposits.—There are three very important reasons for rejecting the idea that meteoric waters can form large ore bodies. These are: (1) *meteoric waters are normally very weak solvents*; (2) *the average rock contains only minute traces of the more valuable heavy metals*; and (3) *underground waters must occupy the larger divisional openings in the rocks and therefore do not have access to all portions*. There is much evidence in support of these points, but they can be considered only briefly here.

Meteoric Waters Are Poor Solvents.—The average meteoric water of springs and wells contains very few substances that aid its solvent power. Carbon dioxide, the most abundant constituent, forms one of the weakest of acids. The stronger ones are absent or present in limited amounts, except in solutions resulting from the breaking up of sulfide deposits, and these are not normal meteoric waters. Meteoric waters are cold, which is another reason for their low solvent power. Very few become heated, and those that have have not given rise to ore deposits.

The Small Quantities of Metals in the Average Rock.—The average composition of igneous rocks (see Table 2, p. 22) and the percentages of the rare elements in the crust (Tables 3 and 4, pp. 23, 24) show unequivocally that the economically important metals are present only in traces in the average rock. The highest estimate for lead (probably excessive) in the average rock is 0.04 pound per ton (12+ cubic feet). To concentrate this amount into a workable deposit is not impossible, given time enough; but it is highly improbable under any conditions. One great difficulty would be the very high insolubility of lead.

The Low Porosity of Rocks.—One of the most faulty conceptions in the field of geology, today, concerns the amount of pore space and other small openings in rocks. The pore space in rocks consists largely of capillary openings in which water *does not circulate*. The water that *moves* through rocks follows the large divisional openings in them. M. F. Fuller estimates that the average vertical joints (and not all joints are water channels) in rocks are from 3 to 7 feet apart and die out rapidly downward. Water may penetrate the capillary openings of rocks, but once there it remains there. How it is possible to concentrate minerals into an ore deposit unless the solution after dissolving them moves out of the places where they occurred is not satisfactorily explained by the supporters of a meteoric origin. One wholly inadequate explanation given is that the metals moved outward by diffusion through the solution.

Summary.—Meteoric waters are weak solvents; yet, to form ore deposits, they must dissolve the merest traces of minerals many of which are highly insoluble. To come in contact with these minerals, moreover, the solutions must circulate through impervious rocks. Circulation in rocks takes place only in the divisional openings, which are normally several feet apart. Under certain physical conditions, as where the rocks are greatly shattered, water may find its way about freely. The average meteoric water, however, is of no value in giving rise to important ore bodies, save where it works upon previously formed ore deposits (such as disseminated deposits) or where it forms residual deposits at the surface.

Methods by Which Downward-moving Solutions Concentrate Ores.—

The dominant work of downward-moving solutions is in reworking the materials in the mantle rock and primary mineral deposits (possibly, also, secondarily enriched ore deposits). One phase of this reworking is the concentration of materials already in these deposits, which may be accomplished in two ways: (1) *by leaching out the worthless materials associated with the ore minerals* and (2) *by dissolving the metal and redepositing it in a more concentrated form*. The first method results in a residual deposit of insoluble minerals at the surface (already discussed) or in a deposit of insoluble minerals below the surface, as the iron ores of the Lake Superior region. The second method is best illustrated by the enrichment of a copper deposit.

Relative Effectiveness of Sulfuric and Carbonic Acids.—The downward transportation of a metal is most effective when the solutions contain acids. These may be carbonic acid, sulfuric acid, and very rarely others. Sulfuric acid is much more effective than carbonic acid, for the carbonates of the common metals are generally more insoluble than the sulfates. The relative solubility of the carbonates and sulfates of the common metals is shown by the following table:

TABLE 9.—RELATIVE SOLUBILITY OF THE ANHYDROUS CARBONATES AND THE SULFATES OF THE COMMON METALS¹

Carbonates	Amount (grams) soluble in 100 g. water at 18°C.	Sulfates	Amount (grams) soluble in 100 g. water at 18°C.
PbCO ₃	0.0001	PbSO ₄	0.0041
Ag ₂ CO ₃	0.00017	Ag ₂ SO ₄	0.5500
ZnCO ₃	0.00047	CuSO ₄	19.3000
FeCO ₃	0.0730 ²	FeSO ₄	23.0000
CuCO ₃.....	.....	ZnSO ₄	53.1800

¹ Lindgren, "Mineral Deposits," p. 929, 1926.² Saturated with CO₂ at 7 atmospheres.

Sources of Sulfuric Acid in Meteoric Waters.—The oxidation of pyrite is regarded as one of the most common sources of sulfuric acid in meteoric solutions, although the oxidation of other sulfides may produce it, also. The simplest reaction for the oxidation of pyrite is as follows:



As the change actually occurs, however, there are several stages; and such intermediate products as sulfur dioxide, hydrogen sulfide, and sulphur are formed. The sulfuric acid liberated unites with most of the metals and other substances present to form sulfates of varying degrees of solubility. In deposits that contain an abundance of sulfides (as many mineral deposits of magmatic origin do), much sulfuric acid will thus be formed.

TYPES OF SECONDARY ORE DEPOSITS FORMED BY DOWNWARD-MOVING SOLUTIONS

There are three classes of secondary deposits formed by downward-moving solutions: (1) *residual*, (2) *oxidized ores*, and (3) *secondarily enriched sulfide ores*. All three types are not necessarily present in a single deposit, and they vary much in economic value. The character of the rock, the degree of shattering it has undergone, and the distribution of the primary minerals all influence the character of the final deposit. The mineralogy and the relationship of the three zones of formation to one another are shown in Fig. 27.

Residual Deposits.—During the process of weathering, the minerals (whether primary or secondary) that are insoluble in the meteoric solutions are left behind and concentrate at or near the surface. This residual material over a mineral deposit is known as "gossan" (Fig. 27) or "iron hat." The concentration of the valuable insoluble minerals contained in about 100 feet of an original deposit into a zone a few feet thick would greatly enrich that zone (see Fig. 28).

Gold, the iron oxides, cerargyrite (silver chloride or horn silver), galena, and quartz are the usual minerals in these deposits. Only the gold, silver, and lead of such deposits are valuable.

It will be seen that this type of deposit grades into the residual insoluble type already discussed. It is included here, also, however,

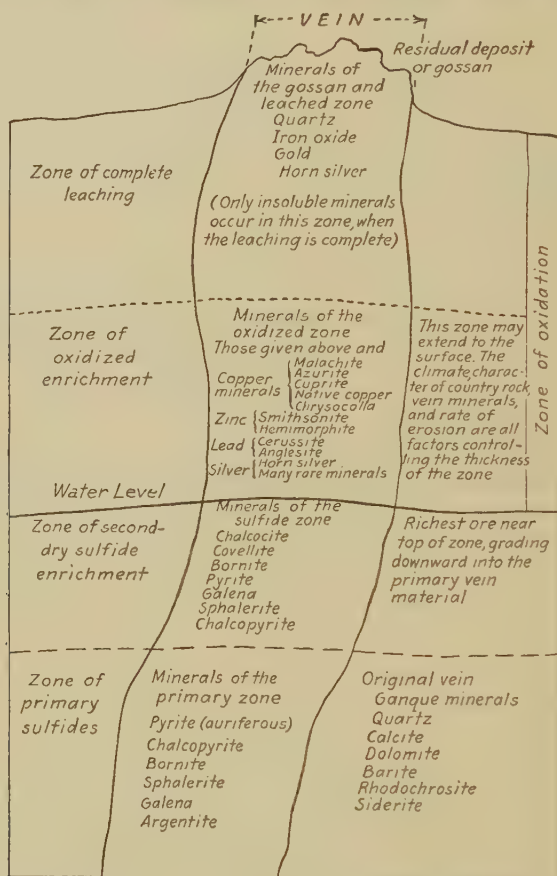


FIG. 27.—Ideal sketch of the various zones in a complex quartz-copper vein. In addition to copper; lead, zinc, gold, and silver occur in the deposit but in small amounts. By changing the proportions of the minerals, the diagram would illustrate enrichment of other metals.

for the sake of completeness in the sequence of the list of deposits formed by downward-moving solutions.

Deposits of Oxidized Ores.—The zone between the surface of the earth and the water level is the zone of active (vadose) water circulation. The solutions coming down from above normally contain oxygen. In this zone, then, precipitation of oxides, carbonates, sulfates, silicates, and even native metals occurs.

Among the minerals found in the oxidized zone are *native copper*; *native silver*; *native gold*; *smithsonite* (zinc carbonate); *hemimorphite* (zinc silicate); *cuprite* (copper oxide); *malachite* and *azurite* (copper carbonates); *chrysocolla* (copper silicate); some *iron oxides*; *cerussite* (lead carbonate); and, very rarely, *anglesite* (lead sulfate). Any of these minerals (except anglesite) may form important ore deposits. Deposits of cerussite are not very common, though an abundance of carbonates in solution may cause its formation in considerable amounts. Very rich deposits of oxidized ores of copper, zinc, and silver are known.

Deposits of Secondarily Enriched Sulfide Ores.—Secondary sulfide enrichment in ore deposits is of outstanding significance. The detailed study of a large number of deposits, during recent years, has revealed the fact that secondary sulfide enrichment was the all-important factor in converting many low-grade metalliferous deposits into workable ore bodies. This is especially true of copper deposits. Silver and zinc undergo sulfide enrichment but much less extensively than copper. Lead, as would be expected from its high insolubility, does not undergo sulfide enrichment. The lead, as galena, is left behind in the residual deposits.

The oxidation of a mass of sulfides of various metals results in the formation of metallic sulfates. These are, notably, iron, copper, and zinc sulfate all of which are easily soluble (see Table 9, p. 73). These soluble sulfates are carried downward until they reach the saturated zone below the water level. There is a deficiency of oxygen in this zone; hence, the primary sulfides there are unoxidized. A very important chemical law then comes into operation, that of the varying affinities of the metals for sulfur. Certain metals have strong affinities for sulfur and once combined as sulfides remain in that form. Mercury and lead (forming, respectively, cinnabar and galena) are good examples of such metals. Other metals give up their sulfur easily. Iron (forming pyrite) is the principal one of these, but zinc and copper also give up their sulfur to a stronger metal. The order of the affinity of these three important metals for sulfur is (strongest first): copper, zinc, and iron. If, therefore, a copper solution (usually copper sulfate) comes in contact with pyrite, the sulfur of the pyrite unites with the copper, and the iron combines with the sulfate. The copper sulfide is deposited and the iron sulfate remains in solution. The common occurrence of pyrite, which furnishes

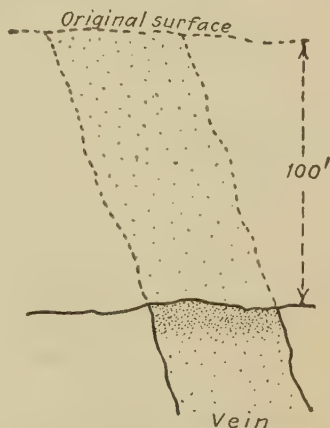
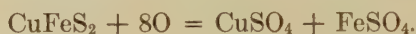


FIG. 28.—Diagrammatic sketch to illustrate how the insoluble minerals of a vein are concentrated in a narrow zone (shown by heavy stippling).

so much sulfur for secondary-sulfide enrichment, is, therefore, undoubtedly the biggest factor in such enrichment.

The Secondary Sulfide Enrichment of a Copper Deposit.—As secondary sulfide enrichment is so largely confined to copper deposits, the sequence of events in the enrichment of a copper deposit will be given. The most abundant copper sulfide is chalcopyrite, CuFeS_2 , the oxidation of which is as follows:

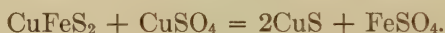


The copper sulfate formed is carried downward [the ferrous sulfate is largely oxidized to ferric hydroxide, $\text{Fe}(\text{OH})_3$] and, after passing below the water level, enters the zone of primary sulfides. Either of the two common copper sulfides: covellite, CuS , or chalcocite, Cu_2S , may form.

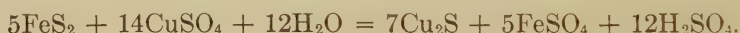
The reaction for the formation of covellite is as follows:



As chalcopyrite contains iron, the following reaction may take place:



Chalcocite is more abundant as a secondary sulfide than covellite. The following is a common reaction for its formation:



The chalcocite replaces pyrite; and, if the action continues long enough, the pyrite will be completely replaced. The continued downward movement and precipitation of copper results in the formation of a body of chalcocite (and covellite) just below the water level. As chalcocite contains nearly 80 per cent copper, its presence to the extent of 2 or 3 per cent in a deposit makes a good copper ore.

Occurrence of the Three Types of Alteration in One Deposit.—All three types of alteration just discussed are not necessarily present in any one deposit, although they are quite commonly so. During the early days of mining in western United States, residual deposits of great richness were frequently found, below which occurred (especially in the southwest) great rich bodies of oxidized ores (usually of copper but also silver and lead). As these ores were exhausted and mining went deeper, the enriched copper sulfide ores were found. Later, due to improvements in mining and milling practice, it was possible to work the low-grade disseminated deposits of the secondary copper sulfide ores. These are known as “porphyry coppers” because of their common occurrence in porphyries. Sulfide enrichment has not taken place in all deposits, and in some not even oxidized minerals are found over the primary ores.

The Function of Secondary Alterations.—Secondary alteration of some kind is a common phenomenon, but it does not always produce

mineral deposits of ore grade. Numerous metals and minerals undergo some change by meteoric waters, but the fact that there are probably no important ore deposits wholly of meteoric origin is evidence that these waters are efficient in concentrating metals *only after magmatic waters have effected a first concentration*.

A given deposit may undergo repeated alterations, becoming so completely changed that the original is unrecognizable. The difficulty of explaining the origin of such deposits is great.

ARE PRIMARY SULFIDE DEPOSITS EVER FORMED BY METEORIC WATERS?

The question, already touched upon, as to whether any important sulfide deposits are of meteoric origin merits further discussion. Although a magmatic origin is agreed upon for most ore deposits, the origin of a few important deposits of simple mineralogy and no evident connection with an igneous mass is still open to dispute. These deposits include the lead deposits of southeastern Missouri; the zinc-lead deposits of Oklahoma, Kansas, and Missouri (and Arkansas); the zinc-lead deposits of the upper Mississippi Valley; several European deposits; and certain copper deposits.

It is impossible to review here all the evidence for the magmatic and meteoric theories. A magmatic origin is believed to explain these concentrations better than a meteoric, however. Especially is this true for the lead deposits in Missouri, Kansas, Oklahoma, and Arkansas. The discovery of every deposit in Missouri (where mining first took place) was of *galena at the surface*, where it had been concentrated by the removal of the other materials. It is, therefore, impossible to accept the view that the traces of lead in rocks were dissolved by meteoric waters (under conditions outlined above) and formed into large deposits of lead ores, when, in the leaching of a deposit containing galena, the galena is practically always left behind. It is admitted by all students of ore deposits that galena does not undergo sulfide enrichment, which is further evidence against a meteoric origin, as it is just another case of the inability of meteoric waters to dissolve galena. Zinc may undergo sulfide enrichment; but, in the deposits of the Oklahoma-Kansas-Missouri area, there was an insufficient supply of pyrite or other sulfides to have permitted sulfide replacement. Attempts have been made to account for the formation of the zinc sulfide by having it precipitated from meteoric waters by hydrogen sulfide, but it is as difficult to explain the source of the hydrogen sulfide as it is to account for the presence of the zinc. The presence, furthermore, of both lead and zinc must be accounted for, as they occur in the same deposit, and the improbability that lead can be concentrated by meteoric waters has been pointed out above.

It is more probable that these deposits are genetically connected with underground sources and that the solutions from the igneous mass arose along broken zones and deposited their metals near the surface. The lead in southeastern Missouri occurs below veins of barite, and barite is found typically in shallow-zone deposits. An intrusive mass no more than 2,000 feet below the surface could have furnished solutions capable of forming any and all of these deposits, as in other regions solutions have formed veins the vertical dimensions of which are 3,000, 5,000, and 10,000 feet. In the deposits of unquestioned magmatic origin, solutions are believed to have penetrated 2,000 feet horizontally from the intrusive and still have been able to alter the rocks. The requirements for the deposits of the Missouri and adjoining areas do not necessarily call for such distances. The difficulty of accounting for the lead-zinc deposits of the upper Mississippi Valley other than as magmatic deposits is similar to that encountered in explaining those of the Tri-State area.

REGIONALLY METAMORPHOSED MINERAL DEPOSITS

Our story of mineral deposits, thus far, has presented the methods of their primary formation and secondary alteration, two processes which have given rise to most of the mineral deposits that furnish materials for man's use. There is still a third method, however, by which changes are produced in mineral deposits of all types. This method, known as *regional metamorphism* (as opposed to contact metamorphism), consists of changes due to great pressure and high temperature aided by the work of solutions. It is called regional metamorphism because the change takes place over a wide area. This type of metamorphism is going on in the zones below those in which the formation of most of the above-discussed deposits took place, but during mountain-making processes, it may approach close to the surface.

Metamorphic Rocks.—Igneous rocks predominate in the deeper part of the earth's crust, as sediments only rarely reach depths of 10,000 or 15,000 feet. The regional metamorphic processes thus operate largely upon the igneous rocks, and, as a result, gneisses and schists are the dominant metamorphic products. Wherever the sediments are involved in regional metamorphism, they are converted into marbles, slates, quartzites, and schists. These changes involve some new chemical combinations and take place in obedience to the law of stability. Also, the individual grains of a rock shift into a position where they can resist the crushing effect of the pressure. The shifting brings about a parallel orientation of the grains, and thus develops the banding so common in gneisses, schists, and slates. So great is the pressure in the zone of regional metamorphism that the rocks flow, and extremely contorted gneisses and schists result.

Regionally Metamorphosed Ore Deposits.—Ore deposits, such as pegmatites, pyritic veins, and even the irregular surface deposits that have become deeply buried, are twisted, warped, folded, and even sheared apart (Fig. 29). As a rule, regional metamorphism does more damage to an ore deposit than good. This does not appear to have been true, however, in the zinc deposits of Franklin, New Jersey, as the value of these seems to have been increased by the rearrangement and recrystallization which the constituent minerals have undergone. Another example of a beneficial change is the formation of specularite by the crystallization of hematite during regional metamorphic processes.

Some gneisses, slates, marble, and serpentine are used for building purposes. Quartzites have some use as granister. Some schists are

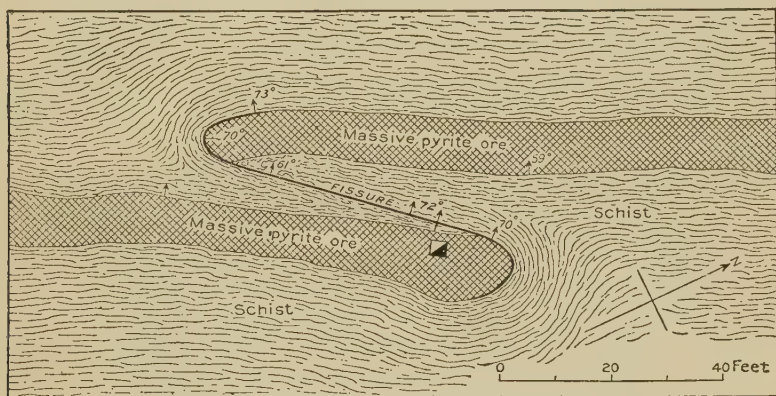


FIG. 29.—A bed of pyrite sheared apart during the regional metamorphism of the deposit. Plan of the ore body on the 115-foot level of the Milan mine, New Hampshire. (Emmons, *U. S. Geol. Survey Bull.* 432, p. 17.)

used for abrasives. Minor materials are garnets, andalusite, mica, emery, and graphite, all occurring in some type of metamorphic rocks. Coal beds may be altered to a graphitic material.

METALLOGENETIC EPOCHS

Mineral deposits are forming all the time, some slowly, others rapidly. We are essentially unaware of their formation even at the surface; for the term "rapid," as we have just used it, means infinitely slow as compared to the average span of a man's life. Weathering is going on at the surface, and new mineral deposits are being formed there. Beneath the surface, where we cannot observe, the processes are going on, also—slowly, where meteoric water is the chief formative agent; more rapidly, where the waters are of magmatic origin. Igneous masses penetrating the outer zone of the earth's crust speed up the process of mineralization

even though no solutions are given off, as the accessions of heat make any solutions already in the rocks more effective mineralizing agents.

Throughout the earth's history, these changes have been going on. There have been periods of marked activity; probably those diastrophic periods that rejuvenated the continents and formed mountains were especially favorable times for such changes. Even though the diastrophism took place slowly, however, it must have been accompanied by movements of magmas that brought about mineralization. The time relationships of these major physical events (earth movements, magma movements, and mineralization) still remain problems to be solved. Between these periods were intervals of quiet during which the formation of surface deposits progressed nicely, as deposits due to leaching, enrichment, and evaporation would form best when the surface was stationary.

If we glance down the geologic time scale, we find that there were apparently major periods of mineralization. The Lake Superior and probably the Brazilian hematite deposits represent long intervals of quiet during which the ores developed by sedimentation and subsequent leaching. In the Lake Superior region and in Ontario, however, ore deposits resulting from igneous activity also are found in the pre-Cambrian rocks. These are the native copper deposits of Michigan; the nickel-copper deposits of Sudbury, Ontario; the silver deposits of Cobalt, Ontario; and the gold deposits of Porcupine, Ontario. What the time relationship of these sedimentary and magmatic ores is we do not know.

During the relatively quiet periods of the Paleozoic era, sedimentary processes were most effective; and salt, gypsum, iron ores, phosphates, coal, oil, and potash deposits were formed.

The diastrophic events at the close of the Paleozoic period were accompanied by intensive mineralization in Europe, but none in America. During this period, many of the important ore deposits of England, Spain, France, Germany, and other countries were formed.

Various types of mineral deposits were formed during the Mesozoic era; but the climax of mineral deposition came in late Cretaceous times, when a period of marked igneous activity occurred accompanied by the formation of numerous deposits of the valuable metals. Extensive mineralization occurred in the western part of the United States during this period.

The igneous activity of the Tertiary age was accompanied by another period of mineralization throughout western North and South America. Gold, silver, and mercury were the principal metals deposited.

This brief review of some of the major events of the earth's history shows that mineralization is going on all the time in varying degrees. It also shows that the physical state of the earth is the controlling factor. The state of the earth is forever changing, yet the tendency is toward the concentration of like substances; and man has discovered and utilized

these concentrations in creating the modern world with its infinite adaptation of these resources to his convenience and pleasure.

SUMMARY OF THE ORIGIN OF MINERAL DEPOSITS

The attempt has been made in this chapter to follow the development of mineral deposits from their primary source as materials in a magmatic mass deep within the earth through to the final stages of their development into various types of deposits. Deposits originating directly from a magma are designated as primary mineral deposits. Some primary deposits are valuable enough to mine; others furnish the material for further enrichment.

The second step in the story of mineral deposits is their alteration at the surface by the agents of weathering into secondary mineral deposits, some of which are economically valuable, depending upon the amount of enrichment produced.

All primary and secondary mineral deposits could be altered by regional metamorphism; but, because the deposits formed near the top of the crust are rarely deeply buried again, only those formed at considerable depths are ordinarily affected by it. This type of alteration furnishes few ore deposits.

Somewhere in this sequence of events, every known mineral deposit must fit. The majority are easily located, but others have been formed by two or more processes, and these are difficult to place. Still others possess a mineralogy so simple that a study of it does not readily reveal the genetic relationships of the deposits. Thus, there is still much opportunity for research in the field of the origin of mineral deposits.

Selected Readings on Principles of Ore Deposition

- BAIN, H. F., and others: "Types of Ore Deposits," Min. and Sci. Press, 1911.
- BECK and WEED: "Nature of Ore Deposits," McGraw-Hill Book Company, Inc., New York, 1909.
- BEYSCHLAG, VOGT, and KRUSCH: "The Deposits of the Useful Minerals and Rocks," Macmillan and Co., Limited, London, 1916.
- CLARKE, F. W.: Data of Geochemistry, U. S. Geol. Survey *Bull.* 770.
- EMMONS, W. H.: "The Principles of Economic Geology," McGraw-Hill Book Company, Inc., New York, 1918.
- KEMP, J. F.: "The Ore Deposits of the United States and Canada," McGraw-Hill Book Company, Inc., New York, 1906.
- : Problems of Metalliferous Veins, *Econ. Geol.*, vol. I, pp. 207–232, 1906.
- LEITH, C. K.: "The Economic Aspects of Geology," Constable, London, 1922, and Henry Holt & Company, New York, 1922.
- LINDGREN, WALDEMAR: "Mineral Deposits," McGraw-Hill Book Company, Inc., New York, 1928.
- RASTALL, R. H.: "The Geology of the Metalliferous Deposits," Cambridge University Press, Cambridge, 1923.
- RIES, H.: "Economic Geology," John Wiley & Sons, Inc., New York, 1925.

- SPURR, J. E.: "Geology Applied to Mining," McGraw-Hill Book Company, Inc., New York, 1926.
- : "The Ore Magmas," McGraw-Hill Book Company, Inc., New York, 1923.
- U. S. Mineral Resources*, published annually.
- VAN HISE, C. R.: A Treatise on Metamorphism, U. S. Geol. Survey *Mon.* 47.
- WALLACE, J. P.: "Ore Deposits for the Practical Miner," McGraw-Hill Book Company, Inc., New York, 1908.

PART II
METALLIC EARTH MATERIALS

CHAPTER IV

IRON

The iron age (which has been outlined in Chap. II, p. 11) began about 7,000 years ago, but most of the modern uses of iron have been developed within the last 100 years. By the time America was discovered, nearly all the European races had developed methods of recovering the metal from its ores and had used it widely in small quantities for making household articles, tools, vehicles, and weapons. So the search for iron in America began as soon as settlers arrived.

Early History of Iron in the United States.—According to our available information, the first smelting of iron in the United States occurred in Virginia in 1608. A small furnace was erected in that state in 1620 but was destroyed two years later by the Indians. In 1645, a small blast furnace was completed at Lynn, Massachusetts, from which iron was successfully produced from a bog-iron ore. Small quantities of iron were also produced in Rhode Island, Connecticut, New Jersey, and Pennsylvania during the seventeenth century. Numerous small furnaces and bloomeries were erected in various parts of the colonies between 1700 and 1750. Furnaces for making pig iron were erected west of the Appalachian Mountains shortly after 1790, and by 1825 they had appeared in many states.

First Production of Steel in the United States.—The outstanding event of this early period was the first production of steel by Samuel Higby and Joseph Dewey in 1728 in Hartford County, Connecticut. The yearly production for a long time, however, was always small. Eighty-two years later, in 1810, only 917 tons of steel was produced in the United States.

Introduction of Railroads.—The building, in England in 1825, of the first railroad in the world created a new and larger demand for iron, as it was used for rails, rolling stock, and engines. The first railroad in America, built in Maryland between 1828 and 1830, employed horsepower for transportation. The first locomotive used in this country was imported from England in 1829 and was run on a railroad in Wayne County, Pennsylvania. By 1830, real railroad building had begun in the United States. That year, there was 23 miles and in 1840, 2,818 miles of railroad. Locomotives were made and used in the United States shortly after 1830. Railroad building, of course, caused an expansion of the iron and steel industries, and rolling mills for making

flat and round iron bars, iron rails, and numerous other articles came into existence.

Introduction of Coke in the Iron Industry in United States.—During the early period, charcoal was used in making iron and steel, but in 1835, coke was successfully employed for this purpose by William Firmstone at the Mary Ann furnace in Huntingdon County, Pennsylvania.

New Processes for Making Steel.—The bessemer process for making steel was invented in England in 1856, but its first successful use in the United States was in 1864 by William F. Durfee at Wyandotte, Michigan. The next year, rails of bessemer steel were rolled at Chicago. The

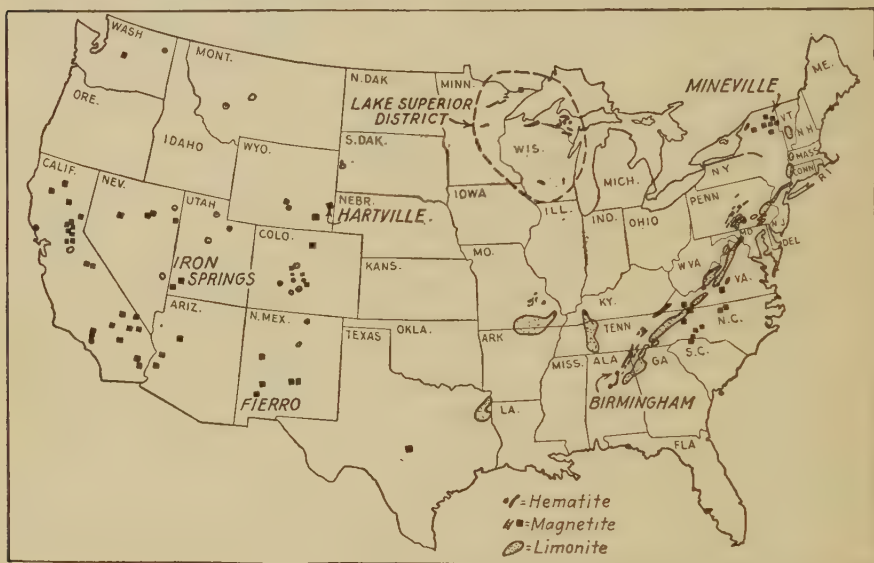


FIG. 30.—Iron deposits of the United States.

Siemens open-hearth process of making steel was invented (also abroad) in 1864 and was introduced into the United States by the New Jersey Steel and Iron Company at Trenton, New Jersey, in 1868. These two processes made possible extensive manufacture of steel rails for railroads, and in the early seventies steel rails rapidly began to replace the old iron ones in the United States.

First Use of Steel and Iron in Constructing Ships, Bridges, Buildings, and Machinery.—The use of steel and iron for making ships and bridges began in the late sixties and developed rapidly during the next decade. Then followed their use in building construction and making innumerable new types of machinery. The iron and steel industries thus entered a period of rapid expansion.

Early Sources of Iron.—Iron deposits of all sizes and of varying degrees of purity were widely scattered over the eastern part of the

United States and were the chief sources of iron ore until the discovery, on Sept. 16, 1844 (by William A. Burt), of the iron ores of the Marquette Range in the Lake Superior region. This first discovery was on Seal Lake in the northern peninsula of Michigan, and production soon began. It was about 30 years (in 1877) before the next Lake Superior iron range, the Menominee, was discovered. The Gogebic and Vermilion ranges were discovered in 1884, the Mesabi in 1892, and the Cuyuna in 1911. Deposits of iron occur in many other states (Fig. 30), but the Lake Superior deposits are by far the largest of any in the United States.

Abundance and Form of Iron.—Iron is the most abundant constituent of the earth's body, according to the estimate made by Washington (p. 22). In the outer 10 miles of the crust, it ranks fourth (comprises 5.05 per cent according to Clarke and Washington) in abundance among all materials present. Minerals that contain it are very common (a recent mineralogy lists 220).

Iron is very rarely found in the native state; that occurring in a basalt at Ovivak, Disco Island, Greenland, and in meteorites are the known occurrences. The greater part of the iron in the outer 10 miles of the crust is in the form of *silicates*, *oxides*, *carbonates*, *sulfides*, and *phosphates*. The iron minerals of economic importance are the oxides and, to a minor extent, a carbonate. Aggregates of the iron oxides and the carbonate form all the important iron ore deposits.

Iron Ore Minerals.—In spite of the large number of minerals that contain iron, only four are important as iron ores. Three of these, *hematite* (red ore), *limonite* (brown ore), and *magnetite* (black ore, called, also, "magnetic ore"), are oxides; and the fourth, *siderite*, is a carbonate.

Hematite.—Hematite is composed of iron and oxygen, two parts of iron combining with three parts of oxygen (Fe_2O_3); 100 pounds of pure hematite would contain 70 pounds of iron and 30 pounds of oxygen (Fig. 31). It usually contains, also, some water and small amounts of silica, aluminum, and manganese. Hematite is red, but the crystalline form, specularite, is steel-gray to black. Both can be recognized by the red streak made when a specimen is rubbed on a piece of unglazed pottery. The specific gravity of hematite is about 5, a cubic foot weighing a little over 300 pounds. Various names are applied to this ore, such as *specular*

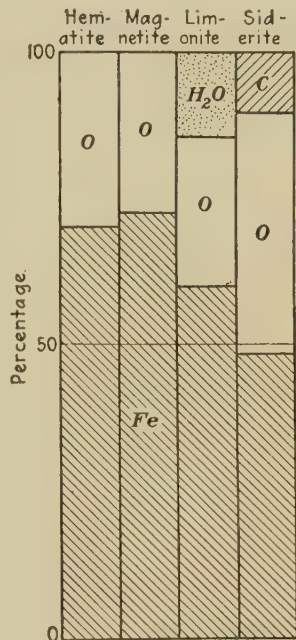


FIG. 31.—The metallic-iron content of the four common iron ore minerals.

ore, fossil ore, oolitic ore, and kidney ore. It is by far the most important iron ore mineral, constituting 95.2 per cent of the iron ore mined in the United States in 1928 (Fig. 32). The chief producing areas in the United States are the Lake Superior region; Birmingham, Alabama; Chattanooga, Tennessee; and Hartville, Wyoming (Fig. 30).

Limonite.—Limonite is composed of iron, oxygen, and water ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$). Because of the water content (which varies from 8 to 15 per cent), the amount of metallic iron in limonite is less than that in hematite. According to the formula, pure limonite would contain 59.9 per cent of iron, 25.7 per cent of oxygen, and 14.4 per cent of water. Limonite is, however, always more or less impure. The impurities are silica, alumina, lime, manganese, and other substances. Limonite is yellow, yellow-

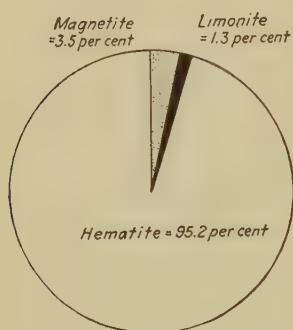


FIG. 32.—Percentage of the total production of each of the chief iron ore minerals in the United States in 1928.

brown to dark brown, or even black. Some hydrated iron oxides having a red to reddish-brown color are included with the brown ores. Limonite leaves a yellow-brown streak on a piece of unglazed pottery. It has a specific gravity of 3.4 to 4, a cubic foot weighing 250 pounds. Limonite mixed with clay is known as "yellow ocher." It is far less important as a source of iron than hematite. It furnished only 1.3 per cent of the iron ore mined in the United States in 1928 (Fig. 32). This production came largely from Alabama, Tennessee, Virginia, and Georgia.

Magnetite.—Magnetite is composed of iron and oxygen in the ratio of three parts of iron to four parts of oxygen (Fe_3O_4). This proportion would give 72.4 pounds of iron and 27.6 pounds of oxygen in 100 pounds of pure magnetite. Impurities, similar to those occurring in hematite and limonite, are present in magnetite, also, but phosphorus and titanium are the most abundant. Magnetite is black and is strongly magnetic, which makes it easy to determine, as no other black mineral is so strongly magnetic. One variety of magnetite is called *lodestone*, because it will attract other substances. The specific gravity of magnetite is about 5, the same as for hematite. Magnetite is slightly more important as an iron ore in the United States than limonite. It constituted about 3.5 per cent of the 1928 production of iron (Fig. 32). It is found chiefly in the Adirondacks of New York and in New Jersey.

Siderite.—Siderite is iron carbonate, FeCO_3 . It contains, when pure, 48.2 per cent of iron, 10.3 per cent of carbon, and 41.4 per cent of oxygen. Silica, alumina, lime, and manganese are common as impurities. Siderite is gray on a freshly broken surface but readily oxidizes to brown after exposure. Its specific gravity is about 3.8. Siderite is frequently

called *black-band ore*, *clay ironstone*, or *spathic iron ore*. It is the least important of the iron ores. Its production in the United States has dwindled from 432,251 tons in 1889 to 1,790 tons in 1928. Most of the production has come from Ohio and Kentucky.

Impurities in Iron Ores.—Silica, alumina, lime, magnesia, manganese, titanium, sulfur, and phosphorus are the common impurities in iron ores. They are removed, as far as possible, during the metallurgical treatment of the ores. Manganese and titanium are not removed in metallurgical processes, and their presence in certain definite amounts produces a steel that is valuable for special purposes. Sulfur and phosphorus in the ore are especially undesirable, because they lessen the strength of the iron or steel. The allowable limit of phosphorous in an ore to be used for making steel by the bessemer process is 0.001 per unit of the metallic iron content; thus, an iron ore containing 62 per cent of iron must contain less than 0.06 per cent of phosphorus. For making pig iron, the amount of phosphorus may be much higher; and in the basic process of treating iron ores, those having a still higher content of phosphorus can be used, as it is removed during the metallurgical treatment.

The following table gives the average composition of all the ore (51,730,000 long tons) shipped from all the ranges in the Lake Superior district in 1927. The high percentage of silica is explained by the fact that the original primary ore was dominantly chert. As mined, the Lake Superior ore is not all of bessemer grade; much of it must go into open-hearth furnaces.

TABLE 10.—AVERAGE COMPOSITION OF THE LAKE SUPERIOR IRON ORES IN 1927¹

Constituent	Percentage
Metallic iron, Fe.....	51.19
Phosphorus, P.....	0.105
Silica, SiO ₂	8.60
Manganese, Mn.....	0.84
Moisture, H ₂ O.....	11.31

¹ Data from U. S. Bur. Mines, 1927.

The Process of Recovering Iron from Its Ores.—The recovery of metallic iron from iron ores involves several processes. These are *mining*; *treatment of ore in a blast furnace to produce pig iron*; and the *further treatment of the pig iron to form the various types of steel*.

Mining.—Iron ores are taken from the ground, either from open cuts on the surface or by underground mining. An ore body that lies near the surface and is sufficiently thick to pay to strip the overlying rock is mined by open-cut methods. Steam shovels are used to handle the ore, and railroad tracks are run in on the level of the ore. Enormous tonnages can be removed rapidly by this method. Where the ore is in beds or veins that extend underground, shafts are sunk, or tunnels are

driven in along the bed or vein and the ore is mined by the various methods used underground.

It is of interest to note that the iron ore produced in the United States in 1927 came from 232 mines of which 131 produced more than 100,000 long tons each. These 131 mines produced 94 per cent of the total production and 10 among the 131 produced more than 1,000,000 long tons each, their combined production amounting to 35 per cent of the total. Of these 10 mines, 6 were in Minnesota, 2 in Alabama, 1 in Michigan, and 1 in Pennsylvania.

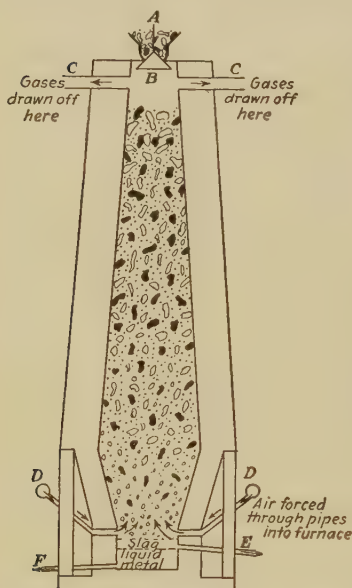


FIG. 33.—Diagram of a blast furnace for smelting iron ore. A, hopper to receive materials for the furnace. B, cone gate, lowered to charge furnace. C, outlet for furnace gases. Materials in furnace are limestone (black particles), coke (white particles), iron ore (stipples). D, pipe to admit air under pressure in furnace (tuyères). E, outlet for draining off slag. F, outlet for removing the liquid iron.

The limestone unites with various impurities in the ore, such as silica and alumina, to form the slag. Much blast-furnace slag is now being used for making Portland cement. The iron as it comes from the blast furnace is called "pig iron." In 1928, in this country, 1,937 long tons of iron ore, cinder, scale, and scrap iron were required to produce 1 gross ton of pig iron. The chief fuel used in the furnaces is coke made from bituminous coal. In 1927, 36,398,000 long tons of such coke was used in the blast furnaces in the United States.

Treatment of Pig Iron.—The pig iron is generally treated by one of several methods. It is made into *cast iron* in a foundry, into *wrought iron*

Metallurgical Treatment.—Iron ore is usually sent directly to the blast furnace as it is mined, but some ores must undergo a certain amount of concentration, and others must be washed before being put into the blast furnace. Only about 13 per cent of the iron ore in the United States has to be pretreated. A blast furnace is a steel tower about 150 feet high (Fig. 33). It is lined with fire brick and has an opening at the top through which the ore, coke, and limestone are introduced. Through a series of holes (called "tuyères") around the furnace near the bottom, hot air is blown in; hence the name "blast furnace." The metallic iron collects at the bottom; the slag, above it. There are openings through which both are removed.

The coke put in with the iron ore unites with oxygen from the air to form carbon monoxide, which has a very strong affinity for oxygen and, therefore, removes it from the iron ore leaving metallic iron.

in a puddling mill, or into *steel* in a bessemer converter or open-hearth furnace.

Cast Iron requires a minimum of treatment for its manufacture. The pig iron is melted in a cupola at the foundry and is poured into the mold of the object to be reproduced as a casting. The amounts of phosphorus, sulfur, and carbon do not need to be controlled so closely as they do in the manufacture of steel, although certain castings must be made of high-grade pig iron.

In making *wrought iron*, the pig iron is placed in a reverberatory or puddling furnace and is stirred (puddled) to remove the phosphorus, silicon, and sulfur. It is removed from the furnace in red-hot, solid masses, called "blooms," and is then hammered into the desired shape. Wrought iron is tougher than cast iron.

Steel is iron that contains a definite quantity of carbon. The maximum amount is 1.5 per cent. Steel that contains more carbon is weakened by a decrease in its toughness, malleability, ductility, magnetic power, and electric conductivity. The greater carbon content also increases the hardness and brittleness of the steel.

The *bessemer process* of making steel is a rapid way of converting a pig iron low in phosphorus and sulfur into a high-grade steel. As the pig iron comes from the blast furnace, it contains silicon, carbon, manganese, and other substances. This liquid is poured into a large barrel-shaped vessel, so arranged as to permit its being tipped down and emptied. Air under pressure is forced up through the liquid iron, and the oxygen of the air combines with the silicon, carbon, and other substances to form a slag over the surface. This process requires from 15 to 20 minutes; and at the right moment, which is just before the oxygen begins to unite with the iron, the converter is turned down and the slag poured off. A definite amount of carbon and manganese is then added, and the air is again blown through the liquid metal for 15 or 20 minutes to mix the carbon and manganese. The product is steel, which is poured into molds, forms ingots, and is then ready for the rolling mills.

In the *open-hearth method* of making steel, the pig iron is placed in a large gas-heated brick chamber, which is lined with certain types of materials. This lining is usually magnesia and lime, because the phosphorus can be eliminated by uniting with the lime and passing into the slag. The carbon of the pig iron is burned to the amount desired and produces a uniform-carbon steel. The open-hearth process makes it possible to use iron ores having a much higher phosphorus content than can be used in the bessemer process; and, as non-bessemer ores are more abundant, the open-hearth-steel now greatly exceeds the bessemer-steel production. Of the 1927 production in the United States, 84.7 per cent was open-hearth steel; 13.8 per cent, bessemer steel; and 1.5 per cent, other classes of steel.

Many ferro-alloys are being manufactured at present (1928). In making them, various metals, such as manganese, nickel, cobalt, tungsten, and titanium, are added to steel to give it special properties for certain uses. These alloys will be discussed in the next chapter.

Mode of Occurrence of Iron Ores.—Iron ores occur in many different types of deposits, due, in all probability, to the persistent character of the iron minerals. The following table shows the most important types of iron deposits, their chief ore and gangue minerals, and where they are found:

TABLE 11.—THE MOST IMPORTANT TYPES OF IRON DEPOSITS

Type of deposit	Iron ore minerals	Common gangue minerals	Regions where they occur
Magmatic segregations	Magnetite	Feldspar, pyroxenes, ilmenite, micas	Lake Sanford, Essex County, New York; Iron Mountain, Laramie County, Wyoming; Taberg, southern Sweden
Contact-metamorphic deposits	Magnetite Specularite	Garnet, epidote, quartz, wollastonite, diopside, other contact-metamorphic minerals	Island of Elba; Fierro, Grant County, New Mexico Iron Springs, Iron County, Utah; Cornwall, Lebanon County, Pennsylvania
Sedimentary iron ores	Hematite, limonite, siderite	Quartz, chert, calcite, clay, dolomite, apatite	Lake Superior region; Clinton iron ores, New York to Albany; Jurassic iron ores of England; oolitic limonite of Lorraine, France
Residual iron ores	Hematite, limonite	Clay, quartz, calcite	Limonite and hematites of the southern Appalachian Mountains Cuba Bilbao, Spain
High-temperature veins	Specularite	Quartz, epidote, garnet, malacolite, fluorite	Iron Mountain, Missouri

Many gradations exist between different types of deposits. Residual deposits may develop from any of the others or from a wholly different type of rock. The common occurrence of magnetite in contact-metamorphic deposits and in magmatic segregations suggests a possible connection between the two types of deposits.

HEMATITE DEPOSITS OF THE UNITED STATES

The hematite deposits of the United States are far more important than are those of all other types. The following graph (Fig. 34) shows the

production of the various types of iron ores in the United States since 1889, which is as far back as good records are available. The overwhelming preponderance of hematite as a source of iron is evident from this chart. The most important districts producing it are shown on the map (Fig. 30, p. 86).

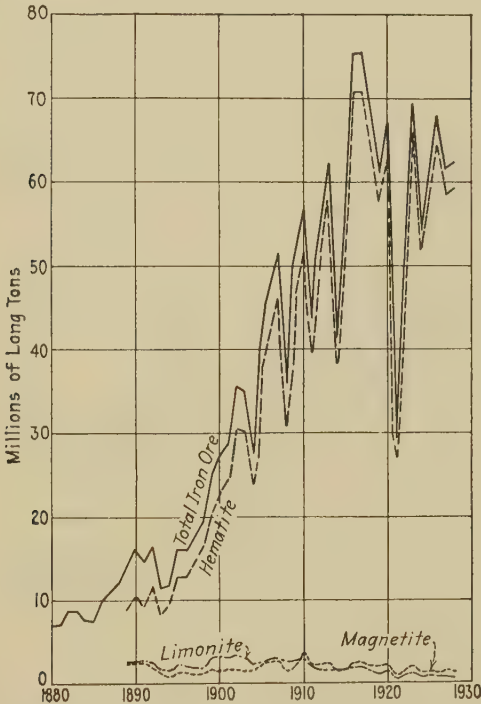


FIG. 34.—The production of hematite, limonite, and magnetite, and the total production of iron ores in the United States from 1880 to 1928. (U. S. Bur. Mines.)

LAKE SUPERIOR DEPOSITS

All the iron ore deposits lying south, west, and north of Lake Superior, in Michigan, Wisconsin, and Minnesota, are included in the Lake Superior district. The districts in Ontario, Canada, belong in the same geological series as those in the United States, but they are much less productive (see Fig. 35).

The Iron Ranges.—The districts are known as “ranges,” because the iron-bearing formations, being a little more resistant to weathering than the other rocks, form slightly elevated topographic features. The most important ranges of the district are the *Marquette* (Michigan), discovered in 1844; the *Menominee* (Michigan), discovered 1877; the *Penokee-Gogebic* (Michigan-Wisconsin), discovered 1884; the *Vermilion* (Minne-

sota), discovered 1884; the *Mesabi* (Minnesota), discovered 1892; and the *Cuyuna* (Minnesota), discovered 1911.

Character of the Iron Formations.—The original iron formations consist mainly of ferruginous cherts in which the iron is in the form of the carbonate siderite and the silicate greenalite, FeSiO_3 . The original formations grade into the iron ores, the intermediate stages consisting of chert containing iron oxides. These formations, which are called "jaspers" and contain 30 to 40 per cent iron, comprise a great volume of rock. The ore, dominantly hematite and limonite, contains about 8 per cent of silica and 10 to 11 per cent of moisture. Nearly one-half of the ore produced in the Cuyuna district in 1927 contained from 5 to 10 per cent of manganese. It was sold separately. The iron-ore formations range in thickness from a few to 1,000 feet. The Biwabik, the



FIG. 35.—Sketch map of the Lake Superior region showing the iron districts and the lake transportation routes.

chief iron-bearing formation of Mesabi district, averages a little over 800 feet in thickness.

Mode of Occurrence of Iron Formations.—The iron formations are sedimentary rocks which are associated with slates, quartzites, conglomerates, dolomites, and various metamorphosed volcanic and other igneous rocks. They have been metamorphosed at their contact with the igneous rocks, the hematite having been converted into specularite and the original iron formation into a magnetite-amphibole rock.

Geological and Geographical Distribution.—The iron-bearing formations all occur in rocks of pre-Cambrian age. The most important deposits are in beds of the Archean era and in Middle and Upper Huronian beds of the Algonkin era. The geological and geographical distribution and the total production of Lake Superior district to the end of 1927 are shown in the following table:

TABLE 12.—THE GEOLOGICAL AND GEOGRAPHICAL DISTRIBUTION OF THE LAKE SUPERIOR IRON-BEARING FORMATIONS AND THEIR TOTAL PRODUCTION TO THE END OF 1927¹

State	District	Production by geological periods, gross tons		
		Archean	Middle Huronian	Upper Huronian
Minnesota.....	Mesabi	.....	.....	781,500,177
	Vermilion	53,255,839	.....	.....
	Cuyuna	.....	.....	18,475,124
Michigan.....	Gogebic-Penokee	.....	.....	166,665,008
	Marquette	.....	162,575,702	.....
	Menominee, Crystal Falls, etc.	.....	.....	157,871,851
				
Wisconsin.....	Penokee	.....	.....	} Included above
	Menominee (Florence)	.....	.....	
	Baraboo	.....	Small	
Totals by periods		53,255,839	162,575,702	1,124,512,160

¹ Modified from Van Hise and Leith, U. S. Geol. Survey *Mon.* 52.

This table brings out the importance of the Upper Huronian formation as a source of iron and, also, the large contribution made by the Mesabi district to the total production of this period.

Structure of the Deposits and Consequent Mining Methods.—The iron formations are strongly folded and crumpled in all the ranges (Fig. 36) except the Mesabi, where they dip gently to the south. Faulting is also common. The ores are associated with synclinal troughs and thus lie at depths as great as 2,000 feet. As a result, mining is by underground methods in all the ranges where folding has occurred. As a rule, the best ore is above the 1,000-foot level, though some mines go down 2,000 feet. The flat-lying ores of the Mesabi range are covered by glacial drift (Fig. 37). The drift is removed by steam shovels and the ores are then mined from an immense open cut. The steam shovels load the ore into ore cars which go directly to the docks. Few of the mines are more than 200 feet deep, although in some the ore goes downward over 400 feet.

Origin of the Ores.—The origin of the great deposits of iron ore of the Lake Superior region has been discussed by geologists for years. Brooks and Pumpelly believed that they were altered limonite or bog-iron ores. Whitney and Winchell and more recently Collins, Quirke, and Thomson regard at least certain of the deposits as being of igneous origin. Van Hise and Leith favor a magmatic source for most of the iron and silica and the deposition of both on the sea floor. Recently, Grout and Gruner have advanced a theory of sedimentary origin for the deposits, that has

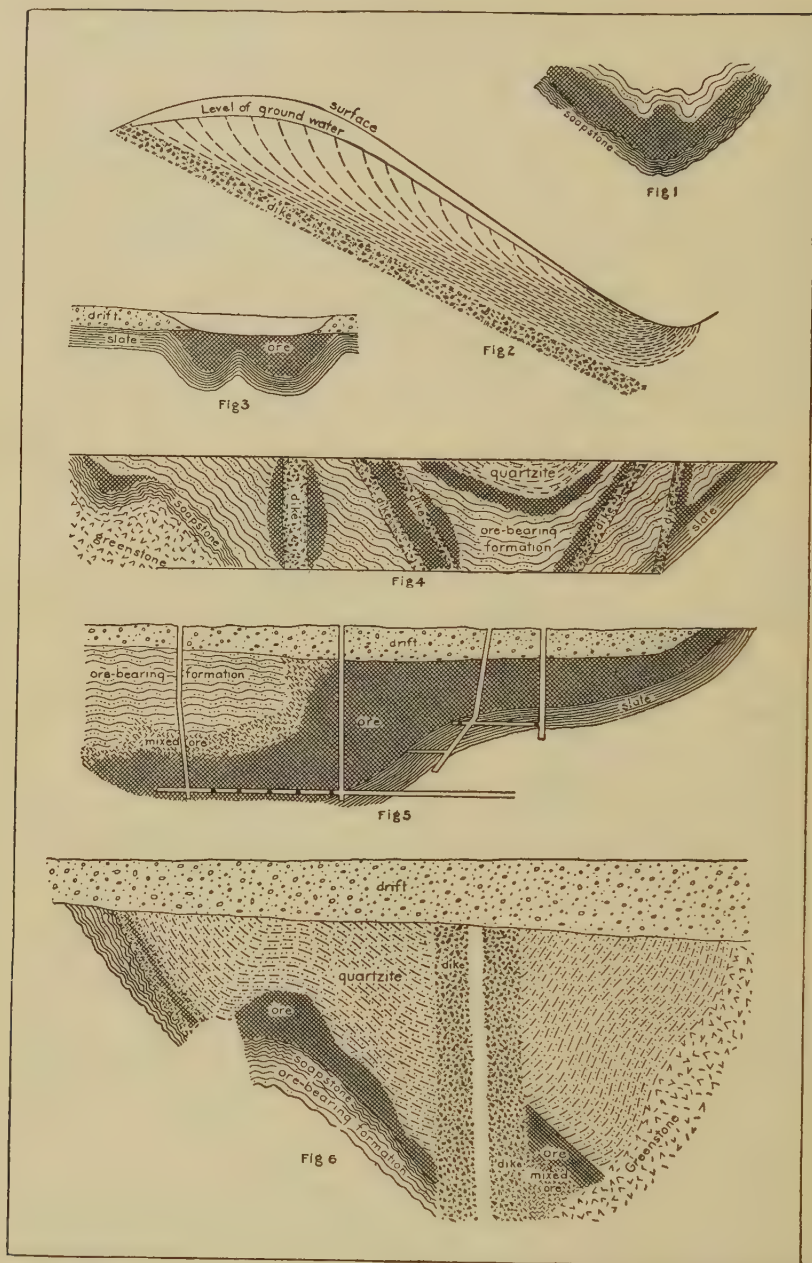


FIG. 36.—Diagrams of the occurrence of the iron ore in the Marquette and Penokee-Gogebic districts of Michigan and Wisconsin: 1 shows the movement of the ground water in the Penokee-Gogebic district, the other diagrams are from the Marquette district; 4 is a generalized section illustrating the numerous methods by which the ores (cross-hatched areas) have developed in synclines adjacent to impervious rocks and along dikes that also controlled the circulation of the water. (Van Hise, U. S. Geol. Survey 21st. Ann. Rept., pt. 4, pl. 54, 1899.)

much in its favor, and the most recent paper on the subject is by Moore and Maynard, who very ably support this hypothesis for most of the stratified ores.

According to the theory of Van Hise and Leith, the iron and silica have been brought upward by magmatic waters from igneous rocks below. These waters reached the surface beneath the sea, and the ferruginous chert was formed by the deposition of the iron as the carbonate and silicate and the rest of the silica as chert. The iron content of these primary ores is about 25 per cent. Other sediments were laid down on this iron-rich member; and, after deformation and erosion, the ferruginous chert was exposed at the surface. The succeeding changes were due to meteoric groundwaters' (carrying oxygen) entering the formations, oxidizing the iron carbonate and iron silicate to hematite

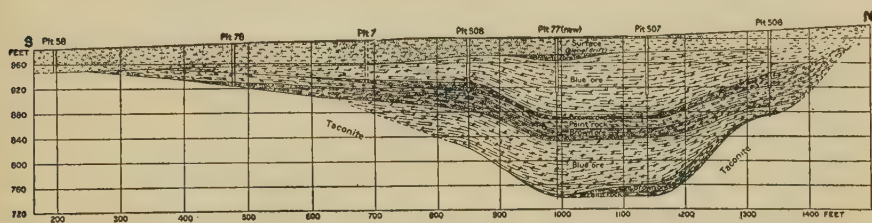


FIG. 37.—North-south cross section of an iron-ore deposit on the Mesabi range near Hibbing, Minnesota, showing the thickness of the glacial drift, the various types of ores and rocks, and the slumping due to secondary concentration. (Van Hise and Leith, *U. S. Geol. Survey Mon.* 52, Fig. 16, p. 180.)

and limonite, and dissolving and removing the associated silica (chert). By these processes, the iron content was raised from the original 25 to 30 or 35 per cent. The enriched formations are the jaspers. The numerous synclinal troughs (Fig. 36) and the impervious soapstones, slates, and quartzites which are interbedded with the iron formations restricted the circulation of the waters to certain channels; and it is in these that the richest ores (ranging from 50 to 62 per cent of iron) are found. The dominant change, after the preliminary oxidation of the ferrous oxide to ferric oxide, was the leaching of the chert. This change was greatly favored by the circulation along the major channels of the synclinal troughs. As pore space developed during the leaching process, the heavy iron minerals slumped, causing further concentration of the ores (Fig. 38). According to this theory of Van Hise and Leith, therefore, the ores are syngenetic sedimentary deposits, and the dominant source of the iron and silica was a deep-seated magma.

The theory supported by Grout¹ and Gruner² is that the iron formations are chemical precipitates of iron and silica which were derived from

¹ GROUT, F. F., *The Nature and Origin of the Biwabik Iron-bearing Formations*, *Econ. Geol.*, vol. XIV, pp. 452-464, 1919.

² GRUNER, J. W., *The Origin of Sedimentary Iron Formations*, *Econ. Geol.*, vol. XVII, pp. 407-460, 1922.

the weathering of the adjacent land mass. If the climatic factors necessary to permit the removal of iron can be satisfactorily explained for these pre-Cambrian periods, this theory has much in its favor, for the presence of silica in all streams is a common phenomenon (see p. 67). That low organisms had much to do with the deposition of the iron, as is postulated, is not so essential, although there is no reason for excluding the effect of bacteria. Both iron and silica are readily deposited chemically.

The recent excellent paper by Moore and Maynard¹ on the origin of the Lake Superior deposits presents the results of a long series of experiments on the solution, transportation, and precipitation of iron and silica. It is shown that both iron and silica can be transported by ordi-

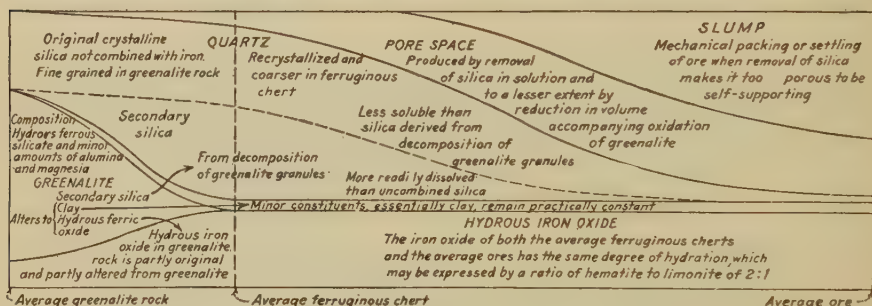


FIG. 38.—Graphic representation of the changes involved in the alteration of greenalite rock to ferruginous chert (taconite) and ore, Mesabi district, Minnesota. The mineral composition of the greenalite rock, ferruginous chert, and ore as represented was obtained by averaging a large number of analyses. (Van Hise and Leith, *U. S. Geol. Survey Mon.* 52, Fig. 20, p. 189.)

nary stream waters and that their deposition is not dependent upon the aid of bacteria or other organic means though organisms undoubtedly played some part in the process. The delayed deposition of the colloidal silica gave rise to the banding which is so typical of the iron ores of the region. Moore and Maynard recognize that magmatic waters could contribute to the materials in an iron formation and probably have done so in certain deposits, but they believe that the typical banded deposits of the Lake Superior region are sedimentary and that the iron and silica came from the weathering of the land.

It is worth noting that all the Lake Superior deposits had undergone the major part of their enrichment before the Paleozoic era began. We know that the Algonkin era covered an enormous period of time and that its major divisions are separated by unconformities that also represent unknown but vast periods. Much time was necessary for the leaching of the relatively insoluble silica, and there is evidence for

¹ MOORE and MAYNARD, Solution, Transportation, and Precipitation of Iron and Silica, *Econ. Geol.*, vol. XXIV, pp. 272-303, 365-402, 506-527, 1929.

believing that it was ample. It is a significant fact that there are other important iron deposits of pre-Cambrian age that owe their concentration to the slow leaching of associated materials over vast periods of time. We have already seen (p. 63) that iron (and aluminum) deposits would predominate at the surface if residual leaching were allowed to go on uninterrupted.

Summary of Origin.—The Lake Superior iron deposits are due to the leaching of the associated materials from an original low-grade iron ore. The iron came from a magma or from the weathering of a land surface under climatic conditions that were favorable to the removal of iron in solution.

Production.—The total production of the Lake Superior district from 1854 to 1927 was 1,340,343,701 long tons of iron. In 1928, the district was responsible for 84.4 per cent of the iron production of the United States and about one-third of the total production of iron in the world. The estimated reserves for Minnesota and Michigan at the end of 1927 were 1,446,892,335 long tons, which is only about 100,000,000 tons (a 2-year production) more than has already been mined.

The Mesabi range, which is the largest producer in the Lake Superior region, is one of the greatest iron-producing districts in the world. It was one of the latest ranges to be discovered, but in 1895 it went into first place in production in the district. In 1927, the Mesabi produced 32,866,034 long tons of iron, which was 64 per cent of the Lake Superior production and about 53 per cent of the entire production in the United States. Single mines produce from 2,000,000 to 5,000,000 long tons annually, which is certainly an enormous output.

Transportation Facilities.—The Lake Superior deposits are all situated within short hauls of water transportation (Fig. 35, p. 94). This is fortunate, as water haulage is cheaper than rail. Loading docks that are capable of handling large tonnages of ore have been built at Duluth and other points on Lake Superior. The ore goes by boat to the furnaces at South Chicago, Illinois, and Gary, Indiana; and to points on Lake Erie for distribution to the furnaces in Ohio and Pennsylvania.

CLINTON HEMATITE

The next most important iron-bearing formation of the United States is the Clinton (Silurian) hematite ore of the eastern part of the country. The iron ore of this formation is widely distributed geographically, being found at numerous localities from New York to Alabama. The chief producing areas are at Birmingham, *Alabama*; Chattanooga, *Tennessee*; and in central *New York*.

The close association in the Birmingham district of iron ore, coal suitable for making coke, and limestone for flux has caused the growth of an important iron and steel industry in that locality. The district

comprises an area about 75 miles long and 10 miles wide having Birmingham near its center.

Character of the Ores.—All the Clinton ores have a high content of calcium carbonate, which has, however, been removed near the surface through weathering. This leached ore is called "soft ore," and contains about 64 per cent of ferric oxide. The unleached ore (hard ore) contains from 35 to 40 per cent of metallic iron, 14 to 17.5 per cent of calcium oxide, and 13 to 14 per cent of insoluble matter. The average iron content of the ores in 1927 was 36.19 per cent. Because of the presence of the calcium carbonate, the ore is, in part, self-fluxing. The production is now almost entirely from the hard ore, as the soft ore has been largely exhausted.

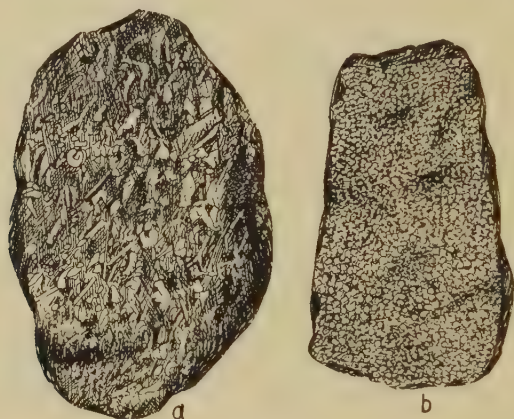


FIG. 39.—Fossil (a) and oolitic (b) Clinton iron ore from Clinton, New York. (After Burchard, Butts, and Eckel, *U. S. Geol. Survey Bull.* 400, pl. 5, p. 26.)

Types of Ores.—The Clinton iron ores are of two kinds, and both are unusual. One type is *oolitic ore* and another is *fossil ore* (Fig. 39). The former consists of rounded grains of hematite, about the size and shape of flaxseed. The oolites consist of nuclei of various materials surrounded by bands of hematite. The fossil ore consists of various kinds of fossils, all more or less fragmentary, which have been replaced and cemented by hematite. The fossil and oolitic varieties may occur in the same bed, but usually one or the other predominates in amount.

Mode of Occurrence of the Ore.—The ore occurs in beds or lenses interbedded with shales, limestones, and sandstones. The number of beds of iron ore is variable, and three or four may be present in one section. They range in thickness from a few inches to 30 feet, and single beds have been traced for 25 miles along the outcrop. The ores reach their best development at Red Mountain, Birmingham, Jefferson County, Alabama, where there are four seams three of which are workable. The production is mainly from the Big Seam (Fig. 40) of which only 9 to 12

feet is being worked. The ore seams show shale partings in some places, and usually only certain parts of the thicker seams are worked. Sandstones and shales are closely associated with the ore.

Structure and Mining.—The beds dip at various angles, depending upon the geologic structure of the area. In the Birmingham district,

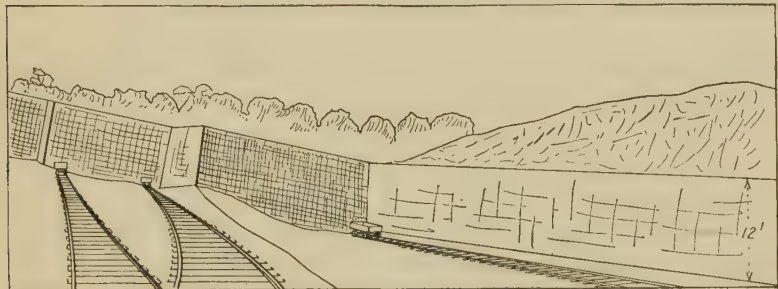


FIG. 40.—The Big Seam iron ore bed of the Clinton at Helen-Bess mine, Birmingham, Ala. The upper 10 to 12 feet of the bed is being mined in this open cut. (After Burchard, Butts, and Eckel, *U. S. Geol. Survey Bull.* 400, pl. 9.)

the dips range from 15 to 40° (averaging less than 30°) to the southeast (Fig. 41). Farther to the southeast, the dip is less and is even reversed, so that the ore lies in a basin in that region. In other areas, notably in New York, where the folding has been slight, the beds are nearly horizontal.

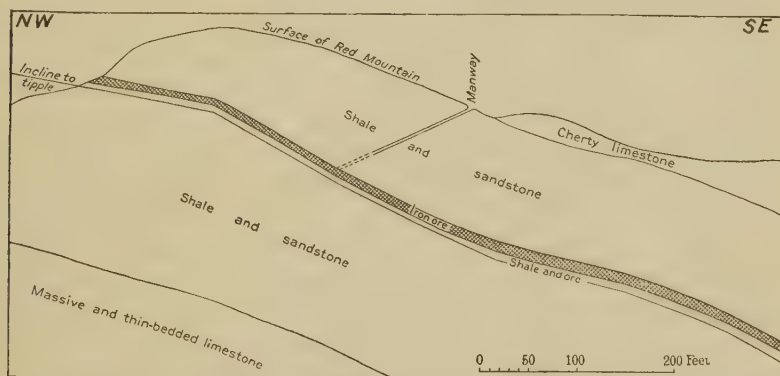


FIG. 41.—Profile of Red Mountain, Birmingham, Alabama, showing the iron-ore bed, the structure, and the associated rocks. (Burchard, Butts, and Eckel, *U. S. Geol. Survey Bull.* 400, p. 136.)

In all the districts, considerable ore (partly limonite) was obtained from open cuts in the earlier periods of mining, but today, most of the mining is by underground methods. Many of the mines in the Birmingham district are now reaching the ore by shafts located from 1½ to 3 miles southeast of the outcrop. These shafts range in depth from 1,400 to 2,000 feet.

Origin of the Clinton Iron Ores.—The origin of the Clinton ores has caused considerable discussion. The following theories have been advanced at various times:

1. Residual enrichment.
2. Replacement.
3. Sedimentary origin (syngenetic).

Residual Enrichment.—According to the theory of residual enrichment, the ores were formed by the leaching of the associated calcium carbonate. This process has formed the soft ores, but that all the ores are due to leaching is no longer believed.

Replacement.—According to the replacement theory, the iron ore was formed through the replacement of beds of limestone by iron oxide brought in by solutions. The fact, however, that the limestone beds in the sections above and below the ore are unaltered; the dominantly bedded character of the ores; and the occurrence of fragments of the ores in overlying beds of limestone are sufficient proofs that the ores antedated the deposition of the overlying beds and, hence, cannot be the result of the leaching of iron (always difficult) from overlying beds.

Sedimentary Origin.—It is now generally believed that the Clinton ores were deposited in shallow water in long, narrow lagoons or bays. During weathering, the iron was taken into solution, largely as the colloidal ferric hydroxide, and was carried to the sea by streams. This could have been accomplished on a land surface that was undergoing chemical denudation. When the solution reached the lagoon or bay, precipitation of the iron was brought about by the electrolytes in the sea water, as has been shown by Moore and Maynard. Apparently, the conditions at one time favored the formation of fossiliferous ore and, at another, the formation of oolitic ore. An abundance of granular nuclear materials would favor the formation of oolites, and an abundance of shelled organisms might result in the formation of fossiliferous ore.

Conclusions as to Origin.—The uniform composition of the hard ore at all depths below the weathered zone and the physical and structural features of the ore point to original deposition as the mode of origin. The presence of fragments of the ore in the beds above also favors the syngenetic origin, as it shows that the ore must have been formed before the deposition of those beds.

HEMATITE DEPOSITS OF HARTVILLE, WYOMING

Hematite deposits of considerable value occur in Platt County in the east-central part of Wyoming. They lie in an area of pre-Cambrian rocks, which consist of interbedded schists, quartzose beds, limestones, and metamorphosed igneous rocks. All the rocks have been folded, crumpled, and brecciated.

The ore, which consists of a more or less hydrated hematite, occurs as lenses along or near the contact of a schist with a limestone below. The lenses conform to the structure of the rocks, and some of them are 1,000 feet long.

Origin of the Hartville Ores.—Ball¹ states that the Hartville ores have replaced the schist. He believes that the iron was leached from the overlying schists (which contain magnetite and pyrite), was carried downward along the limestone footwall, and was precipitated by oxygen-bearing waters from another source. One cannot but wonder, however, why the limestone was not more readily replaced than the schists.

IRON MOUNTAIN, MISSOURI

A deposit of specular hematite occurs in the pre-Cambrian rhyolite porphyries at Iron Mountain, St. Francois County, Missouri. The first deposit worked consisted of boulders of specular hematite which were

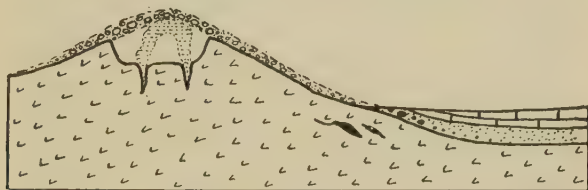


FIG. 42.—Sketch of Iron Mountain, Missouri, showing the open cut on the top of the hill, the original vein, the conglomerate ore (on the slope) derived from it (both now exhausted), and the conglomerate ores at the base of the Cambrian sediments. Black area represents hematite.

scattered over the surface of a small hill; hence the name "Iron Mountain." Large veins of the specular ore were found in the porphyries beneath the boulders and were worked until exhausted. A good bed of conglomerate ore occurs at the base of the Cambrian beds, resting on the pre-Cambrian (Fig. 42).

The deposits are high-temperature veins formed by the replacement of the porphyry along irregular fissures. Epidote, quartz, malacolite, and garnet are the chief gangue minerals.

MAGNETITE DEPOSITS OF THE UNITED STATES

Magnetite is a minor source of iron in the United States, furnishing only about 3 to 3.5 per cent of the iron ore mined. The annual production of magnetite for the last 30 years has ranged from 1,000,000 to 2,500,000 long tons. There are two classes of magnetite ore; one is free from titanium and the other is titaniferous. The titaniferous ores have only a small value, because they are so refractory (hard to fuse) that the

¹ BALL, SIDNEY H., The Hartville Iron-ore Range, Wyoming, U. S. Geol. Survey Bull. 315, p. 190, 1907.

cost of producing iron from them is excessive. Minor quantities are used in making some special grades of steel.

Magnetite occurs in two general types of deposits: one, a *regionally metamorphosed deposit*; and the other, a *contact-metamorphic deposit*.

REGIONALLY METAMORPHOSED MAGNETITE DEPOSITS

Deposits of Eastern United States.—Important magnetite deposits in regionally metamorphosed rocks occur from the Adirondacks in New York to Alabama. The major production comes from *New York* and *New Jersey*, and a small production from *North Carolina*.

The magnetite in these areas occurs as lenses in metamorphic rocks which are generally gneisses and schists but may be marbles and other metamorphosed sedimentary rocks. The longer axis of the lenses is

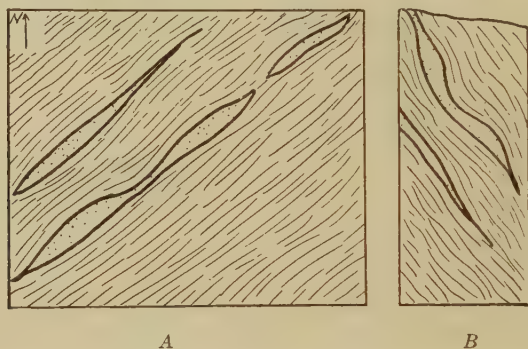


FIG. 43.—Ideal sketch of lenticular magnetite ore bodies occurring in schists. A, plan of ore bodies. B, section.

parallel to the foliation of the rocks (Fig. 43). The lenses range from 10 to 200 feet in thickness, and some are several thousand feet long. Lenses of lean ore have been traced for five or six miles. Swells and pinches are very common. The ores may have sharp boundaries (Fig. 44), or they may grade into the associated metamorphic rocks. The gangue minerals are those commonly found in metamorphic and igneous rocks, namely, feldspar, quartz, and ferromagnesian minerals. At Mineville, New York, considerable apatite occurs with the ores. This apatite is removed in order to lower the phosphorus content and is then sold for fertilizer purposes. Magnetite ores have a wide range in iron content, and when the amount of iron falls below 50 per cent, they must be concentrated. The magnetic property of magnetite is made use of in the concentration of the ores. As the latter dip steeply, mining is carried on by underground methods.

Origin of Regionally Metamorphosed Magnetite Deposits.—Early studies of these magnetite ores led to the conclusion that they were sedimentary deposits which had undergone metamorphism. Their

occurrence in metamorphic rocks of sedimentary origin was favorable to this conclusion; and, for the ores which are not associated with igneous rocks, as in certain parts of the Grenville series, it would seem that the conclusion is correct. Kemp and Newland showed some years ago, however, that most of the deposits in the Adirondacks are associated with igneous rocks and probably represent magmatic segregations. The form of the deposits and the abundance of apatite present are favorable to this view. The presence of the apatite and fluorite has also been regarded as an indication of an origin by magmatic waters, in which case the ores would have been introduced into the metamorphic rocks. The deposits



FIG. 44.—Open-cut portion of a magnetite mine at Mineville, New York, showing the thickness of the lenses of ore (in pillars) and their sharp contact with the enclosing metamorphic rocks.

in New Jersey are also held by Bayley to be of magmatic origin. The author of this volume believes that the ores at Mineville, New York, are metamorphosed sediments.

CONTACT-METAMORPHIC MAGNETITE DEPOSITS

Several contact-metamorphic deposits of magnetite occur in the United States, mostly in the western part. The most important of these are at Cornwall, Lebanon County, *Pennsylvania*; near Iron Springs, Iron County, *Utah*; Fierro, Grant County, *New Mexico*; Heroult, Shasta County, *California*; and Eagle Mountain, Riverside County, *California*.

The Deposits of Fierro, Grant County, New Mexico.—The magnetite deposit at Fierro, New Mexico, occurs at the contact of a quartz diorite porphyry with a Paleozoic limestone (Fig. 45). The ore bodies are irregular, tabular masses of magnetite and some hematite. They lie

close to the porphyry. Typical contact minerals, such as garnet, epidote, and pyroxene, are common. Chalcopyrite is locally abundant. The ores are being shipped to the smelter at Pueblo, Colorado. In 1927, the ore averaged 51 per cent iron and 0.65 per cent manganese.

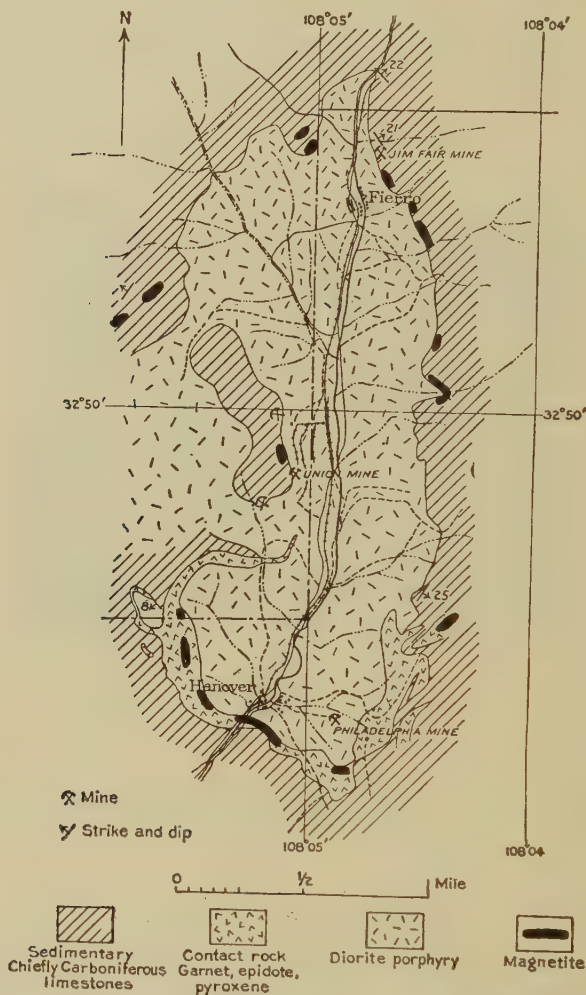


FIG. 45.—Map showing geologic relations in the Fierro iron-ore district, New Mexico. Modified to show magnetite deposits. (Paige, *U. S. Geol. Survey Bull.* 380, p. 200.)

The Deposits near Iron Springs, Utah.—A deposit of magnetite is located in Iron County in southwestern Utah. Rocks of Paleozoic and Tertiary age are cut by laccolithic intrusions of a felsitic rock (andesite), and the ores are in the limestones at the contact with this rock. They occur, also, in fissure veins in the igneous rock (see Fig. 14, p. 43). The

main ore body, which roughly follows the contact, consists of magnetite and hematite and a little limonite. The iron content of the ores averaged, in 1927, about 52 per cent. The gangue minerals are calcite, quartz, chalcedony, and garnet and other silicates. These ores are typical contact-metamorphic deposits. The iron and other materials were introduced with the igneous mass.

The Deposits at Cornwall, Lebanon County, Pennsylvania.—The Cornwall magnetite deposits occur in a calcareous shale at its contact with a thick sill of diabase. The solutions forming them penetrated several hundred feet into the calcareous shale, depositing, besides the ores, a series of contact-metamorphic minerals. These deposits have been worked for years and have produced over 1,000,000 tons of ore. Before concentration, the ore averages 37.7 per cent iron; after concentration, 56.55 per cent. Like the New Mexico deposits, these contain some chalcopyrite.

TITANIFEROUS MAGNETITE DEPOSITS

Deposits of titaniferous magnetite occur in *New York, Minnesota, and Wyoming*.

The deposits at Lake Sanford, Essex County, New York, and at Iron Mountain, Laramie County, Wyoming, are the largest. In both localities the ores occur in association with anorthosite, an igneous rock composed dominantly of basic plagioclase feldspars. The ores represent magmatic segregations. They form irregular masses in the rocks; or, where they have been injected into the rock from below (as most of them apparently have been), they form veins. The titanium is present in ilmenite, FeTiO_3 , which occurs intergrown with the magnetite. The gangue minerals are those found in basic igneous rocks, namely, the ferromagnesian minerals and the lime-rich feldspars. The iron content of the ores has a wide range.

LIMONITE OR BROWN-ORE DEPOSITS IN THE UNITED STATES

The brown ores consist of various forms of hydrous iron oxides the chief of which is limonite. The limonite deposits have originated in several ways: (1) as *bog deposits*, (2) *sedimentary deposits*, and (3) *residual deposits*.

Bog-iron ores were used to a limited extent by the early colonists in America, but there are no important deposits of them in the United States. Though *sedimentary limonite* is an important iron-ore mineral in Europe, no deposits occur in the United States. These two types of iron ore are of interest, as they represent deposits made from iron in solution. The removal of iron in solution during weathering requires very favorable climatic and physical conditions and so does not occur very often.

Residual Limonite Deposits.—Deposits of residual limonite occur in all parts of the United States, but the production comes largely from the southern Appalachian states, especially Alabama, Tennessee, Virginia, and Georgia. In the west, Colorado and Utah produce a small amount. The iron content of these ores is always low, ranging from 35 to 55 per cent. Much of the ore mined must be washed and concentrated. Clay, quartz, and calcite are the common impurities. Residual limonite ores have been formed through the weathering of ferruginous rocks or iron-rich ore deposits, such as pyrite.

Deposits of the Western States.—Residual limonite is fairly common throughout the western states, where it occurs above various metalliferous deposits. The limonite deposits are rarely worked for their iron content but are sometimes used as fluxes in blast furnaces, especially if they contain small amounts of such metals as gold and silver, which can be recovered in the final refining. A few of these deposits are valuable for their manganese content, as, for instance, those at Leadville, Colorado, which averaged 1.38 per cent of manganese in 1927. Such deposits (gossan) are found at Leadville; Niehart, Montana; the Black Hills, South Dakota; and several places in Utah, Nevada, and New Mexico.

Deposits of the Southern Appalachian States.—The usual residual limonite ores overlie such rocks as limestones, sandstones, and more rarely shales. These rocks contain varying amounts of iron. The largest deposits occur in the southern Appalachian region, where two types, mountain ores and valley ores, are found. The former occur as pockets of irregular size just above the Lower Cambrian quartzite and the latter as equally irregular masses in the clay over a limestone. Some of these masses may contain several hundred thousand tons of ore. The mountain ores follow the upper surface of the quartzite to a depth of several hundred feet.

Both types of ore are believed to have originated through the weathering of iron-bearing rocks some of which contained siderite and possibly some pyrite. The iron, of course, was readily oxidized and easily concentrated along with the other insoluble materials of the original rock, mainly clay and quartz. The widespread occurrence of brown ores is undoubtedly due to the fact that weathering always tends to concentrate the iron oxides at the surface. Deposits are rare in the recently glaciated area of the United States, because the ice swept away any residual accumulations that had been formed, and the subsequent period has been too short to allow for the formation of extensive deposits. The important deposits, therefore, occur in the region south of the glaciated area.

IMPORTANT FOREIGN IRON DEPOSITS

Iron ore deposits are scattered all over the world, but the majority of them are small. Their geographical distribution is shown on the

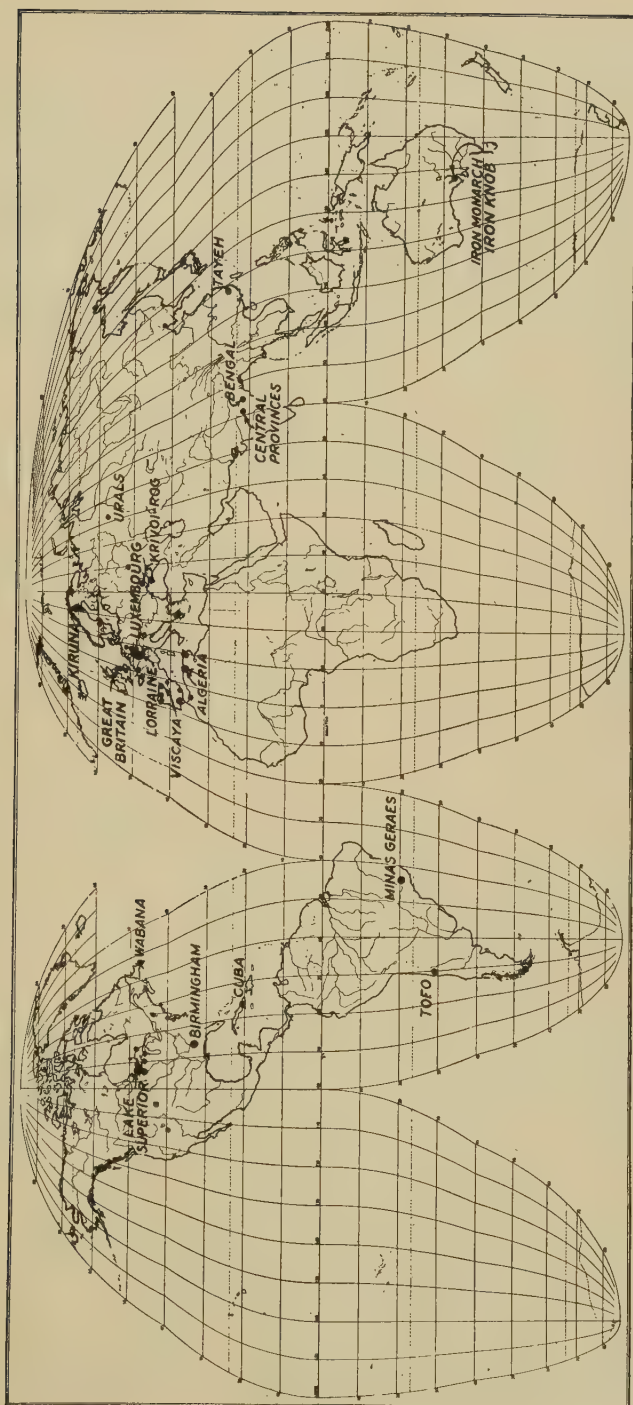


Fig. 46.—The important iron deposits of the world. The chief producing areas are named.

world map of iron deposits (Fig. 46). The major part of the world's iron ore comes from the United States, France, Germany, Great Britain, Sweden, and Luxembourg.

The total iron ore reserves of Europe are large. The major production at present (1928) comes from the *Lorraine field* in *France, Germany, Luxembourg, and Belgium*. The Lorraine ores are *sedimentary limonites*, or "minettes," and cover a large area. About 55,000,000 metric tons of these ores was mined in 1927.

Sweden has large deposits of *magnetite* at Kiruna, Gellivare, and Tuolluvarra in the northern part of the country and smaller deposits in the southern part. She produced nearly 10,000,000 metric tons of iron ore in 1927.

The bedded, *oolitic siderite* of Jurassic age occurring at Cleveland Hills in Yorkshire (the most important iron-producing area in Great Britain), Lincolnshire, Northamptonshire, Leicestershire, and in Scotland is the chief source of iron in *Great Britain*. There is a large reserve of these ores.

Cuba has very large deposits of *residual hematite* that have been producing for nearly 50 years. They occur in the northeastern part of the island.

The Wabana *hematite* deposits of *Newfoundland* are large and are steady producers. The ores are of sedimentary origin.

Brazil has enormous reserves of very high-grade *hematite* ores. They occur in Minas Geraes and cover an area of about 100 square miles. They are of sedimentary origin.

Spain is rich in *hematite* deposits, but they have been worked only moderately. They are widely scattered. The Bilbao district in Viscaya in northwestern Spain is an important producer.

Other countries that have important deposits of iron ore are *Russia, Austria, Algeria, Tunisia, Australia, and India*.

USES OF IRON

We look upon iron as so common that we are apt to forget how essential it is to our daily life. If all the iron in use by man were to be suddenly removed, it would mean the collapse of modern civilization, and man would again be thrown upon his own resources as he was back in the stone ages. This change might have its advantages if he could make use of the experience he has gained in modern life. Of all the various metals in use today, iron is undoubtedly the most indispensable.

No attempt will be made here to list the uses of iron. Each of the three common forms in which it is employed, *i.e.*, cast iron, wrought iron, and steel, has its own particular field, though the uses of steel far exceed those of the other two. Steel has an infinite range of uses in making machinery of every description, in constructing railroads,

bridges, ships, skyscrapers, building materials, and articles for the home. It has long been known, however, that iron has its limitations, in not being perfectly adapted to every purpose to which it has been put. In recent years, attempts have been made to improve its qualities for certain purposes by alloying it with other metals. These ferro-alloys vary widely in their physical and chemical properties, and they have extended the field of iron's usefulness.

A total of 48,000,000 tons of steel was made in the United States in 1926, and it has been estimated in *The Iron Age* that this amount was distributed among the various major industries as follows:

TABLE 13.—DISTRIBUTION OF THE 1926 STEEL PRODUCTION OF THE UNITED STATES AMONG THE VARIOUS INDUSTRIES

Industry	Percentage
Railroads.....	23.5
Building and construction.....	19.5
Automotive.....	14.5
Oil, gas, and water production; mining.....	9.5
(Exports).....	5.0
Machinery construction.....	4.0
Agriculture.....	4.0
Manufacture of food containers.....	4.0
All others.....	16.0
Total.....	100.0

The outstanding importance of the first three industries in the use of iron is evident from the table.

We are extravagant in our use of iron. One needs only to note the objects that are rusting away on every hand to realize that this is true. It has been estimated that 4,000,000 tons of iron and steel annually disappear by rusting in the United States. Much of this waste is preventable. One of the important objectives in developing ferro-alloys is to find a cheap method of making a rust-proof iron or steel.

The story of-making high-grade steels for specialized uses is of interest, though it cannot be given here. The methods of converting steel into machinery, automobiles, tools, and household utensils are extraordinarily varied and interesting, yet we scarcely ever give a thought to them as we use the final product.

PRODUCTION AND PRICE OF IRON ORES

Records of the production of iron ore in the United States have been kept since 1810. The annual output since 1880 is shown by the curve in Fig. 34 (p. 93). The total annual production of iron in the United States did not reach 10,000,000 long tons until in 1886. From that year, however, it rose rapidly to its maximum in 1916 and 1917. It was the abnormal demands of war for iron and steel that sent our production soaring in

those years, yet that apex represented only the upward continuation of the normal rate. The drop, following the World War, and the further abnormal drop in 1921 (a year of financial depression in all industries in this country) sent the production to less than half the maximum amount. Recovery followed, but the industry has not again attained the previous high level, and the rate of increase has greatly altered. The course of the mean curve of production at present (1928) suggests that in 1913 it was near the apex and that, had the war not occurred, the curve

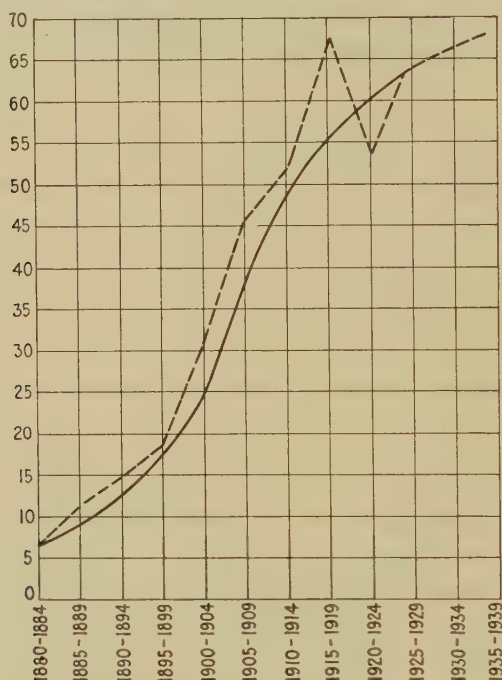


FIG. 47—Curves of the iron production of the United States by 5- and 10-year averages; also trend of future production. (Data from *U. S. Bur. Mines.*)

would have flattened out markedly during the next decade. The actual trend is best shown by averaging the production for a group of years and plotting the mean. This has been done for groups of 5 and 10 years and has been plotted in Fig. 47. The 10-year grouping erases the abnormal features of the war and the depression following. The curve of the annual production shows numerous periods of depression through its course, however, especially after 1900 (Fig. 34, p. 93). This is because the production of iron is a basic industry in that it depends upon the utilization of iron in other industries. Periods of depression in the other industries, therefore, are reflected in the output of iron ore. As hematite is the chief source of iron in the United States, the close parallelism of the hematite curve to the iron-ore curve is what would be expected.

The average price of a long ton of iron ore in 1928 was \$2.46, which is the lowest it has been since 1916, when it was \$2.34 per ton. From 1917 to 1923, the average value was over \$3 a ton, but since 1923 this has suffered a steady decline.

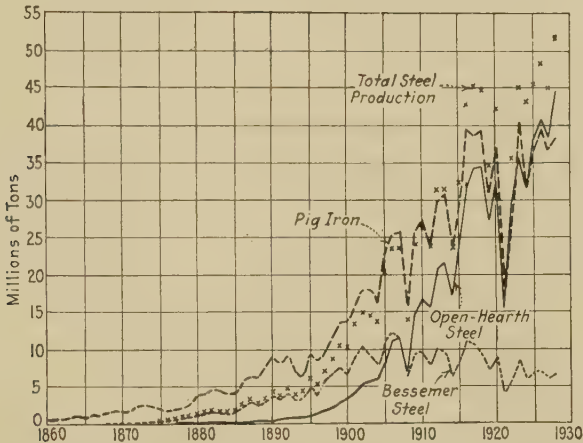


FIG. 48.—Pig iron, bessemer steel, open-hearth steel, and total steel production in the United States from 1860 to 1928. Note that the production of open-hearth steel passed that of bessemer steel in 1908, and that the total production of steel has exceeded the pig-iron production since 1912 (see Fig. 48A). (Data from U. S. Bur. Mines.)

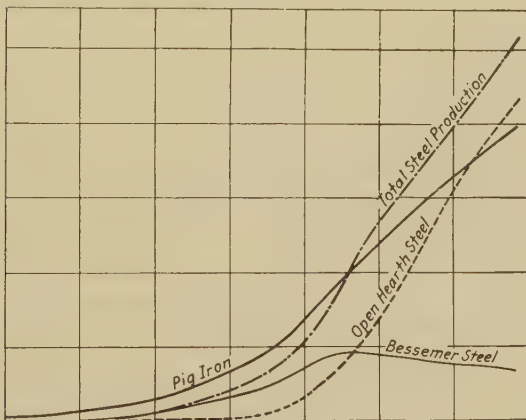


FIG. 48A.—Uniform production curves of pig iron and steels. Drawn from Fig. 48.

The 37,410,897 long tons of pig iron produced in 1928 required in its production 72,447,960 long tons of materials, of which cinder, scale, and scrap iron comprised 6,026,785 long tons. It has already been stated that 1.947 tons of materials are used in making 1 ton of pig iron, and the figures just given show that about 51 per cent of the iron in the ore was recovered. The value of the pig iron shipped from the blast

furnaces in 1928 was \$661,351,270, which was an average price of \$17.27 a ton.

The production of all kinds of steel in the United States in 1927 was 44,935,185 long tons of which 38,068,335 was open-hearth steel; 6,191,727, bessemer steel; 666,087, electric-furnace steel; and 9,036, crucible steel. The shift in production from bessemer to open-hearth steel appears in Fig. 48, which also shows the total production of pig iron from 1860 to 1928.

It is significant that the production of steel has exceeded that of pig iron in recent years and that since 1924 that of open-hearth steel, alone, exceeded that of pig iron. The production of steel in 1927 exceeded that of pig iron by 7,524,000 long tons and was slightly more than the average of the peak production during the World War. Yet, 11,630,500

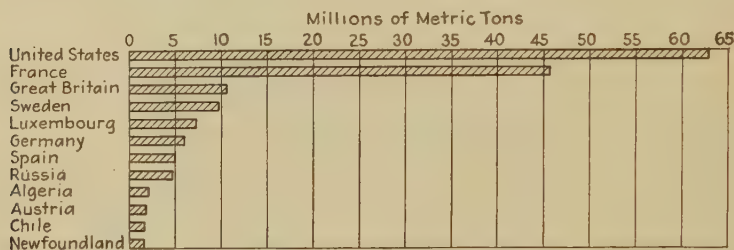


FIG. 49.—Production of iron ores by the leading nations in 1927. (India and Czechoslovakia produced over 1,000,000 metric tons in 1926 but the figures for 1927 were not available.) (Data from U. S. Mineral Resources.)

long tons less of iron ore was mined in 1927 than the average for the above period. Apparently, this difference is accounted for by the utilization of scrap steel and iron by the furnaces. Statistics as to these scrap materials are not collected by the U. S. Bureau of Mines, but the bureau estimates that the scrap available (aside from that reused by the steel plants, railways, and large manufacturing plants themselves) amounts to about 5,000,000 tons. It is evident that the marked use of scrap ferrous materials is an important step toward conserving our iron ores.

No less than 18 states produced some iron ore in 1928, but 96.2 per cent of the production came from 5 states: Minnesota, Michigan, Alabama, Wisconsin, and Pennsylvania (named in the order of their production).

The United States was responsible for 45 per cent of the total world production of iron ores in 1926. Those countries whose production exceeded 1,000,000 metric tons in 1927 are shown in Fig. 49. Although the domestic supply of iron in the United States is adequate for all our needs, 2,620,000 long tons were imported in 1927. Slightly over half of this amount came from Chile; and Africa (Algeria and Tunisia), Cuba, and Sweden

supplied most of the remainder. Exports of iron from the United States (practically all of which went to Canada) amounted to 898,000 long tons.

Selected Readings on Iron

GENERAL

- ECKEL, E. C.: "Iron Ores, Their Occurrence, Valuation, and Control," McGraw-Hill Book Company, Inc., New York, 1914.
- EMMONS, W. H.: "The Principles of Economic Geology," pp. 290-344, McGraw-Hill Book Company, Inc., New York, 1918.
- HARDER, E. C.: Iron-depositing Bacteria and Their Geologic Relations, U. S. Geol. Survey *Prof. Paper* 113, 1919.
- and EDDINGFIELD: Iron, Spurr's "Political and Commercial Geology" pp. 55-89, McGraw-Hill Book Company, Inc., New York, 1920.
- KEMP, J. F.: "The Ore Deposits of the United States and Canada," McGraw-Hill Book Company, Inc., New York, 1903.
- LEITH, C. K.: "Economic Aspects of Geology," pp. 154-173, Henry Holt & Company, 1921.
- LINDGREN, W.: "Mineral Deposits," pp. 401-419 and numerous other pages, McGraw-Hill Book Company, Inc., New York, 1928.
- Mineral Industry*, issued annually.
- Mineral Resources of United States*, 1908, Part 1, pp. 81-123.
- Ibid.*, 1910 and other years, Part 1, pp. 71-116.
- RASTALL, R. H.: "Geology of the Metalliferous Deposits," pp. 312-361, Cambridge University Press, 1923.
- RIES, H.: "Economic Geology," pp. 502-567, John Wiley & Sons, Inc., New York, 1925.

SPECIAL

Lake Superior district:

LEITH, C. K.: Mesabi District, U. S. Geol. Survey *Mon.* 43, 1903.

VAN HISE and LEITH: Lake Superior District, U. S. Geol. Survey *Mon.* 52, 1911.

The best description so far published.

Clinton iron ores:

BURCHARD, BUTTS, and ECKEL: The Birmingham, Alabama, District, U. S. Geol. Survey *Bull.* 400, 1910.

NEWLAND and HARTNAGEL: Iron Ores of the Clinton Formation in New York, N. Y. State Mus. *Bull.* 123, 1908.

Hartville, Wyoming:

BALL, S. H.: U. S. Geol. Survey *Bull.* 315, p. 190, 1907.

Iron Mountain, Missouri:

CRANE, G. W.: The Iron Ores of Missouri, Mo. Bur. Geol. and Mines, vol. X.

Magnetite deposits:

BALL, S. H.: Iron Mountain, Wyoming, U. S. Geol. Survey *Bull.* 315, p. 206, 1907.

KEMP, J. F.: Adirondack Titaniferous Ores, U. S. Geol. Survey 19th *Ann. Rept.*, Part 3, p. 377, 1899.

KEMP and NEWLAND: Iron Ores of Adirondacks, N. Y. State Mus. *Bull.* 119, 1908.

LEITH and HARDER: Iron Springs, Utah, U. S. Geol. Survey *Bull.* 338, 1908.

SINGEWALD, J. T., JR.: The Titaniferous Iron Ores of the United States, U. S. Bur. Mines *Bull.* 64, 1913.

CHAPTER V

FERRO-ALLOY METALS

As we have seen in our discussions of iron and steel, carbon has long been (and still is) the chief element used in converting the former into the latter. Steel, however, has very definite limitations in its hardness, toughness, elasticity, ductility, and other physical properties; and it has been found that the addition of certain rare metals in amounts ranging from one to several per cent not only improves certain of these properties but also contributes valuable new ones.

The chief metals which are thus alloyed with iron are *chromium, cobalt, manganese, molybdenum, nickel, titanium, tungsten* and *vanadium*. Although not discussed here, silicon is used extensively in making ferro-silicon, and phosphorus goes into ferrophosphorus. Steel containing some of these metals has a greatly increased ability of retaining its temper, even when red hot, a quality which permits greater speeds during cutting processes.

In discussing these rare metals together, under the head of ferro-alloys, it must not be thought that they are used only as alloys, for each metal has certain other uses. Some of them, as tungsten, have uses that are fully as important as their employment in ferro-alloys. Grouping these metals together under a common head is done largely for convenience; and they are placed here (following Iron) in order to emphasize their connection with iron.

The magnitude of the uses of ferro-alloys in the United States is evidenced by the production in 1928 of 794,695 long tons, valued at \$66,578,039. The production of the various alloys is given in the following table:

TABLE 14.—FERRO-ALLOYS SHIPPED FROM FURNACES IN THE UNITED STATES, 1928¹

Variety of alloy	Long tons	Value	Value per ton
Ferromanganese.....	310,122	\$29,199,990	\$ 94.15
Spiegeleisen.....	116,911	2,802,108	23.96
Ferrosilicon (7 per cent or more of silicon)....	310,770	15,199,746	48.90
Ferrotungsten.....	1,975	3,195,690	1,618.07
Ferrovandium.....	1,895	5,085,759	2,683.25
Other varieties ²	53,022	11,094,746	
Total.....	794,695	\$66,578,039	

¹ U. S. Bur. Mines.

² Includes ferrochromium, ferromolybdenum, and calcium-molybdenum compounds, ferrophosphorus, ferrotitanium, ferrozirconium, silicomanganese and silicospiegeleisen, and zirconium-ferro-silicon.

CHROMIUM

Chromium is widely distributed in the rocks of the earth's crust and ranks in abundance as the sixteenth element. Its average percentage is very small, 0.037 per cent. Chromium occurs dominantly in magnesium rocks, especially in peridotites. The metal has a wide and important use in alloys.

Mineralogy of Chromium.—There is only one important chromium mineral, and that is *chromite*. Its composition is $\text{Cr}_2\text{O}_3 \cdot \text{FeO}$, and when pure it contains 68 per cent Cr_2O_3 . Some of the Cr_2O_3 may be replaced by Al_2O_3 , and some of the FeO by MgO . The average chromite ore contains between 35 and 55 per cent Cr_2O_3 , but the marketable ore must contain at least 45 per cent. The price of the ore increases as the Cr_2O_3 content increases. Other chromium minerals are known, but they are not important as sources of chromium.

The Properties, Mode of Occurrence, and Origin of Chromite.—Chromite is black, has a hardness of 5.5, a specific gravity of 4.45, and is insoluble.

All chromite deposits are associated with peridotites and pyroxenites or with the serpentine resulting from the alteration of those two rocks. The chromite occurs as crystalline grains scattered through the rock or as lenses and tabular masses. The latter forms may be large enough and rich enough to work, but, as a rule, they have to be further concentrated after mining. The disseminated grains become workable deposits by residual concentration, the very insoluble chromite being left at the surface as the associated rock materials are removed by solutions. The residual ores have produced many important deposits of chromite. A third mode of occurrence of chromium is in chromiferous iron ores. These are of low grade, usually containing from 1 to 3 per cent chromium. Some of these deposits, as those in Cuba, contain several hundred million tons of ore.

All the chromite deposits of the world represent magmatic segregations, the chromite having been separated from the original magma in the manner outlined under Magmatic Segregations (p. 33).

Chief Deposits of Chromite. *Domestic Deposits.*—Chromite is found in numerous places in the United States; but the total production amounts to only a few hundred tons, the large demands of the country being met by imports. Yet from 1830 to 1870, the world's demands for chromite were supplied from the Soldiers Delight district in Baltimore County, Maryland, and other nearby mines; and in 1918, due to the cutting off of foreign supplies and the high price (\$44.99 per ton for 41 per cent Cr_2O_3 ore), the United States led in the production with 82,430 long tons.

Chromite is found in eight states: *California, Maryland, Montana, North Carolina, Oregon, Pennsylvania, Washington, and Wyoming*, and

in *Alaska*. Unfortunately, however, it occurs in some 2,000 small deposits, all of low grade; for the estimated total amount of accessible ore, in 1925, was only 786,100 long tons of ore containing more than 35 per cent Cr_2O_3 . It was further estimated that an additional 466,500 tons might be mined if the demand was great enough. Between 1921 and 1926, small tonnages were produced in five different states of which California was the only one to produce each year. The other states were Oregon, Maryland, Montana, and Washington. The location of the more important chromite areas is shown in Fig. 50.

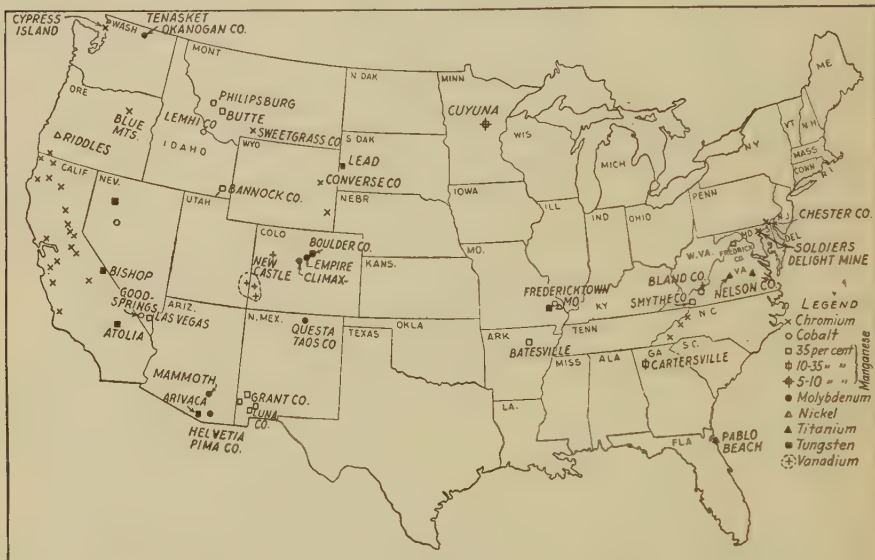


FIG. 50.—Location of the chromium, cobalt, manganese, molybdenum, nickel, titanium, tungsten, and vanadium deposits of the United States.

Foreign Deposits.—Foreign deposits of chromite are widely scattered. The most important ones are shown on the world map (Fig. 51).

The most important of the foreign chromite deposits are those in the Selukwe district, *Rhodesia*, where the ores occur dominantly in talc schist but, also, in other schists and in serpentine. The schists and serpentines were formed by regional metamorphism of peridotites. Some of the tabular ore bodies in the talc schists range from 150 to 400 feet in length and from 25 to 50 feet in width. This ore can be mined and shipped without concentration. The chromite also occurs as seams (veins) in a great serpentine dike, 330 miles long and 4 miles wide. These veins are 4 to 10 inches thick, and some have been traced on the surface for 6 miles. These two types of deposits must represent an enormous amount of chromite. Nearly one-half of the world's supply in 1927 came from

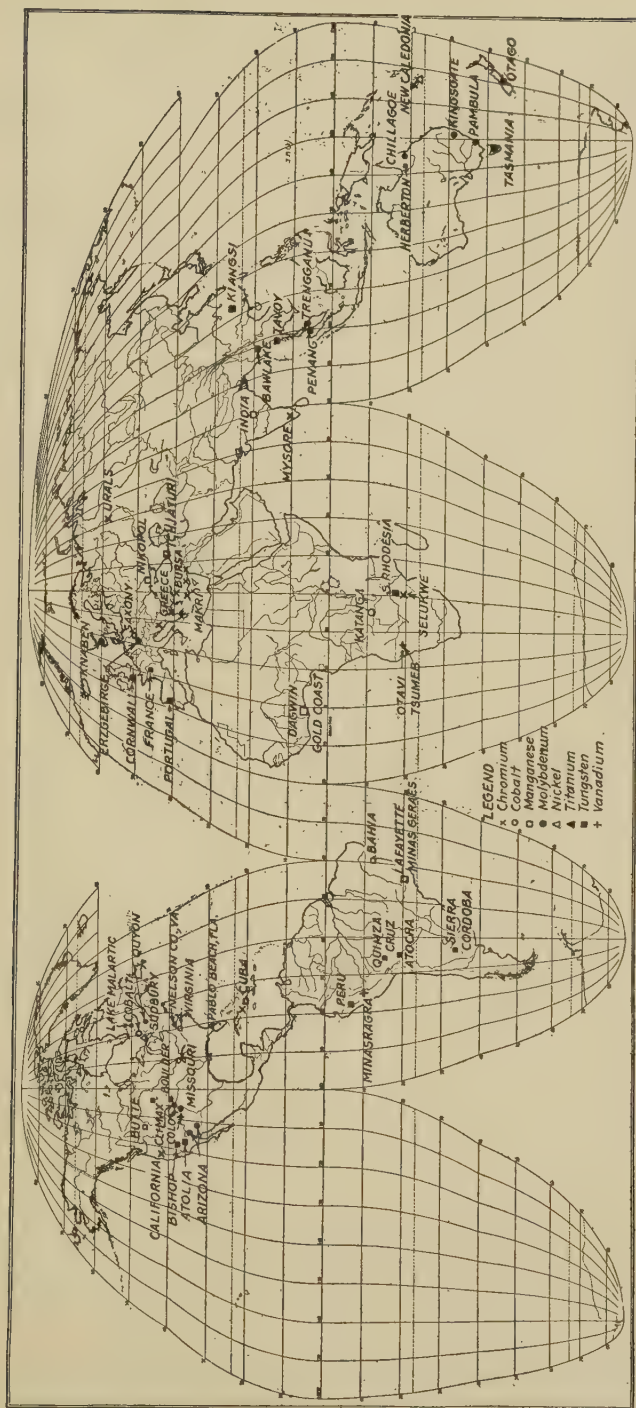


Fig. 51.—Important deposits of chromium, cobalt, manganese, molybdenum, nickel, titanium, tungsten, and vanadium of the world.

them. It is stated that by the end of 1925 no less than 64,000 chromite claims had been located in this district.

The chromite deposits of *New Caledonia* are of both the residual and the solid tabular types. They have long been an important source. The ore is of high grade, much of it averaging 55 per cent Cr_2O_3 . There are also large reserves of ore that can be concentrated.

Valuable deposits of chromite occur in the province of Brusa in *Turkey*. From 1870 to 1903, these deposits of Asia Minor supplied more than half the world's chromite. They are not readily accessible, however, and, as a result, first the New Caledonian and then the Rhodesian deposits have taken the lead in production.

The chromite deposits of *Cuba* are large. They have been opened only recently (1918), but in 1926 they ranked second in production to the Rhodesian deposits. They are associated with serpentine. Enormous deposits of chromiferous iron ores also occur in Cuba, as has been stated.

Other countries containing chromite deposits are *Australia, Greece, Guatemala, India, Russia, Quebec, and South Africa*.

Uses of Chromite.—Few substances have undergone a more surprising change in demand than chromite. The total imports into the United States in 1927 were almost double the world's entire production in 1905; and much of this increased production has occurred since 1922, the imports of the United States in 1928 being 2.4 times as great as in 1922. This increase is probably due to the greater use of chromite for refractories and in producing rustless and stainless steels. The following table shows the distribution of the uses of chromite in 1922, 1925, and 1927:

TABLE 15.—USES OF CHROMITE IN 1922, 1925, AND 1927 IN THE UNITED STATES¹

Use	Percentage in 1922	Percentage in 1925	Percentage in 1927
Metallurgical.....	40	32	46
Refractories.....	35	41	41
Chemical.....	25	27	13
Total.....	100	100	100

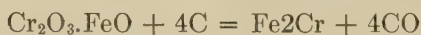
¹ U. S. Bur. Mines.

Refractories.—The use of chromite as a refractory is fully discussed under Refractories (p. 626). For this purpose, it is a strong competitor of magnesite brick. On account of the small amount available and its incalculable importance in metallurgy, it is being urged that chromite should not be employed for uses that dissipate it. When used as a refractory and in some chemical uses, the chromium cannot be recovered. In

metallurgical uses, it is not lost. A substitute for chromium as a refractory should, therefore, be employed.

Metallurgical Uses.—Chromium is extensively used in making *ferrochrome alloys* and, to a lesser extent, *non-ferrous alloys*.

The *ferrochrome alloys* are made in the electric furnace. The charge consists of chromite and anthracite coal. The carbon at a temperature of 1,185°C. or higher unites with the oxygen of the chromite, thus:



The Fe₂Cr is ferrochrome, and it must contain 60 per cent of chromium and practically no carbon.

Ferrochrome is used in making *chrome steel* and chrome iron, as no method has been devised to smelt iron and chromium directly from the ores. In making chrome steel, ferrochrome is melted with the proper amount of iron to give from 2 to 18 per cent of chromium, depending upon the grade of chrome steel desired. When the carbon content of the product is below 0.12 per cent, the alloy is called "chrome iron."

Chrome steels possess great hardness combined with great toughness, a rare combination, as hard steels are ordinarily brittle. The toughness of the steel permits its being bent while cold, and special drills must be used to drill holes in it. Chrome steel can be welded on iron, a process which produces a surface so hard that tungsten-steel drills must be used to drill it. Because of its greater strength, less chrome steel than common carbon steel is needed in making automobile frames; hence, such frames are lighter. A reduction in the size of motors for automobiles and airplanes has been made possible by the use of chrome steel.

Special chrome steels are produced by the addition of certain metals. In making a steel that is to be subjected to abrasion, nickel, vanadium, tungsten, and manganese are added. *Nichrome*, an alloy containing 60 per cent Ni, 14 per cent Cr, and 15 per cent Fe, withstands high temperatures. *Stellite*, an alloy of cobalt, chromium, and tungsten or molybdenum, is a valuable high-speed steel. Some industrial plants, where the tool steel used is a chromium high-speed steel, would have to be 5 to 7 times their present size had ordinary tool steel been used.

A very important use of chromite is in making *stainless steels* which will not rust for a long time. This is one of the uses for which chromite should be saved, as not only can the chromium be recovered from the alloy, but also the iron is thus saved from rusting. At least 10 per cent of chromium is necessary in these rustless steels, and 13 to 15 per cent is more common. A little nickel may be added. Large amounts of cutlery, exhaust valves, turbine blades, pump rods, roller bearings, and electric-heating devices are made from stainless steels. Chrome steels are very resistant to acids, and the steel least affected by them is a chrome-nickel (Cr, 18 per cent; Ni, 8 per cent).

A recently developed use of chromium is for *plating*. Some automobile radiators and other parts are now chromium plated. The coating is hard and white and very resistant to corrosion. Chromium-surfaced plates for engraving last twice as long as those of case-hardened steel and four times as long as those having nickel-coated surfaces. It has been found that chromium-plated electric flat irons require 30 per cent less energy to push than the ordinary irons. Fine chromium wires are made by plating copper wire, drawing it down, replating, and repeating the process until the amount of copper on the interior is negligible.

Chemical Uses.—As seen from Table 15, 13 per cent of the chromite used in the United States in 1927 was used in chemicals. These were primarily chromates and bichromates. Yellow, green, and red chrome



FIG. 52.—Curve showing the production and value of chromite in the United States from 1911 to 1924. Note the stimulus of the high price during the World War. (*U. S. Bur. Mines.*)

pigments are widely employed in paints and dyes. Other chrome chemicals are employed in tanning (they make a very soft and pliable leather), in bleaching fats and oils, and in the ceramic industries.

Production of Chromite.—The production of chromite in the United States in 1928 was 660 long tons, valued at \$14,807. Only 368 tons of the amount sold was mined in 1928, the remainder having been mined in previous years. Figure 52 shows what may be done with low-grade ores when the value of the ore is high enough.

The world's production in 1925 (the last year for which complete figures are available) was 313,793 metric tons of which amount Rhodesia produced 123,220 metric tons.

Imports of Chromite into the United States.—The imports of chromite into the United States steadily increased from 1922 and reached the highest amount, 222,360 long tons, in 1927. In 1928, they were slightly less. The major part of the imports came from Rhodesia, Cuba, British India, Greece, and New Caledonia.

COBALT

Cobalt, though one of the minor constituents of the earth's crust, is of very widespread occurrence. Its estimated average percentage in

the crust is 0.001, and its rank is thirty-third among the other constituents. It is less abundant than nickel, though the two elements are usually associated in their minerals. The possibilities of cobalt in ferro-alloys have not yet been fully developed.

Mineralogy of Cobalt.—Cobalt is present in several minerals, chiefly those containing arsenic and sulfur. Metallic cobalt occurs in small amounts in the iron-nickel meteorites. Most of the cobalt used is recovered from complex ores from which other metals are also produced. In some of the refining processes, it is merely a by-product. The most common cobalt minerals are given in the following table:

TABLE 16.—COMMON COBALT MINERALS

Mineral	Composition	Percentage
Linnæite ¹	Co_3S_4	58.00
Cobaltite.....	CoAsS	35.50
Smaltite.....	CoAs_2	28.20
Erthyrite.....	$\text{Co}_3\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$	29.40

¹ Linnæite often contains as high as 20 per cent nickel (as in the Missouri deposits) and is then called *siegenite*.

Mode of Occurrence of Cobalt.—The cobalt minerals are more characteristic of the intermediate- and shallow-vein deposits than of any other types, though some cobalt is recovered from magmatic segregations and residual deposits. In the largest deposits, cobalt is associated with silver, copper, and nickel; but it may occur, also, with lead and other metals.

Cobalt Deposits.—The two richest deposits of cobalt (both are associated with rich silver ores) are those of Cobalt, Ontario, *Canada*; and of Annaberg and Schneeberg, Saxony, *Germany*. In both these deposits, it occurs in arsenides and sulfides which are associated with a remarkable series of silver minerals. The deposits form well-defined veins. A third deposit of considerable importance is at Joachimsthal, *Bohemia*.

Cobalt is produced during the smelting of the copper ores from Elisabethville, Katanga, *Belgian Congo*; and in small quantities from the nickel-copper ores of Sudbury, Ontario, *Canada*. The Congo ores may contain 2 to 4 per cent.

Smaller deposits of cobalt are those of Cloncurry in Queensland, *Australia*; and Fredericktown, Madison County, *Missouri*. It occurs as siegenite in the Fredericktown deposits. These deposits, which include the oft-cited ones of Mine La Motte, were worked a few years ago but are idle now. Small productions of cobalt ores have been made from Idaho (near Blackbird, Lemhi County) and from Good Springs, Clark

County, *Nevada*. The cobalt deposits of the world are shown in Figs. 50 and 51, pp. 118 and 119.

Uses of Cobalt.—Cobalt has physical properties similar to those of nickel and so produces a similar steel. Its higher cost (\$2.06 per pound in 1927), however, prevents its substitution for nickel (worth about \$0.35 per pound). Cobalt makes a tough, elastic steel. The addition of 3 to 4 per cent of it produces a high-speed steel, which retains its hardness even when the speed of cutting heats it to a red heat. In this respect, cobalt steel is similar to tungsten steel. Nickel does not give this property. Cobalt produces a highly magnetic steel which is used extensively for permanent magnets. Another important use is in making corrosion-resistant steels. Safety-razor blades and surgical instruments made of a cobalt-chromium-tungsten steel have recently been put upon the market. These articles retain their cutting edge indefinitely and also resist corrosion.

The most important use of metallic cobalt is in making the alloy stellite, which is very resistant to corrosion and acids and possesses other special physical properties. High-speed cutting tools, precision gages, and many other instruments are made of stellite. The composition of the stellite alloys varies; a common one contains 60 per cent cobalt, 25 per cent chromium, and 15 per cent tungsten or molybdenum.

Formerly, the most extensive use of cobalt was as a pigment. It imparts a beautiful blue color to pottery, glass, enamel, and other materials. It is employed in various paint pigments. Minor uses of cobalt are as driers in paints; in ceramic industries; as agents for neutralizing the color due to iron; and in making medicines, insect powders, inks, table ware, and hydrometers.

Production of Cobalt.—There is no production of cobalt in the United States. Both production and price are very effectively controlled by foreign interests. Some ore (about 30 tons in 1927) is imported, but most of the cobalt imported is in the form of the metal or the oxide. In 1927, we imported 407,198 pounds of metallic cobalt, valued at \$841,442, and 369,747 pounds of the oxide, valued at \$703,608.

MANGANESE

Manganese is a common and widely distributed metal but only in small amounts. The average manganese content of the outer 10 miles of the earth's crust is 0.09 per cent. Small deposits are widely distributed, but those that are rich enough to mine are not abundant; hence, the major production of the world is restricted to a few areas. Of the metals used in making ferro-alloys, manganese is the most essential one; therefore, the quantity needed is much greater than that of any of the others.

Mineralogy of Manganese.—There is a marked similarity between the common minerals of iron and manganese. The oxides are the most

common minerals for both, and the carbonate and silicate of each occur. The important manganese minerals and their composition are given in the following table:

TABLE 17.—IMPORTANT MANGANESE MINERALS

Mineral	Composition	Percentage of manganese
Pyrolusite.....	MnO_2	63.00 $\pm$
Manganite.....	$\text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O}$	62.40
Psilomelane.....	MnO , $\text{MnO}_2 \cdot 2\text{H}_2\text{O}$	45.00 to 60.00
Polianite.....	MnO_2	63.00 +
Hausmanite.....	Mn_3O_4	72.50
Rhodochrosite.....	MnCO_3	47.60
Rhodonite.....	MnSiO_3	41.90
Bementite.....	$2\text{MnSiO}_3 \cdot \text{H}_2\text{O}$	39.10
Franklinite.....	$(\text{Zn}, \text{Mn})\text{O} \cdot (\text{Fe}, \text{Mn})_2\text{O}_3$	Varies

Physical Properties of the Manganese Minerals.—All the oxides are black; but rhodochrosite and rhodonite, if fresh, are some shade of pink. Bementite is grayish yellow. The oxides vary in hardness from 1 to 6.5. Some are crystalline and others are amorphous. Like the iron minerals, most manganese minerals formed at the surface are amorphous. They probably existed as colloids in the solutions or immediately after being precipitated as the oxides. Crystallization may occur later. The carbonates and silicates are crystalline minerals.

Grades of Manganese Ores.—Manganese ores are extremely variable in composition, and, as a result, several grades are recognized. They are as follows:

	Percentage manganese content
Chemical ores.....	82 to 87
Manganese ore.....	35 or more
Ferruginous manganese ore.....	10 to 35
Manganiferous iron ore.....	5 to 10

A manganese ore must contain 35 per cent manganese as a minimum. For metallurgical purposes, the standard is 46 per cent manganese, not more than 6 per cent iron, 8 per cent silicon, 0.15 per cent phosphorus, and 0.5 per cent sulfur. Only the oxides can be used directly for making ferromanganese (the chief metallurgical product), but the carbonate after roasting can be so used. A certain amount of manganese is recovered as a residue from the zinc ores of Franklin, New Jersey.

Mode of Occurrence of Manganese Ores.—Manganese ores occur as *residual deposits*, *sedimentary deposits*, *vein* and *replacement deposits*, and *regionally metamorphosed deposits*.

The *residual manganese deposits* are of all sizes and shapes. They occur as masses on the surface; in pockets in residual or transported clays; and as pockets replacing the rocks beneath the surface. The best residual ores lie within 100 feet of the surface.

The *sedimentary manganese* occurs as bog deposits on the surface and as bedded ores with shales and sandstones. Some bedded deposits are really nothing but shales containing several per cent of manganese. These deposits must be concentrated to become workable.

The *vein and replacement deposits* are well defined. Their chief minerals are rhodochrosite, rhodonite, and quartz. These minerals and the minor ones may fill the vein or replace the walls, as at Butte and Philipsburg, Montana, or form extensive replacement deposits in limestone, as at Leadville, Colorado.

The *regionally metamorphosed manganese deposits* occur in gneisses, schists, slates, quartzites, and marbles. Some of the deposits must undergo oxidation and enrichment to be valuable; and others, as the manganiferous zinc ores at Franklin, New Jersey, and some of the deposits of India, are rich enough to mine. The bementite deposits of the Olympian Mountains, Washington, are regionally metamorphosed deposits.

Origin of Manganese Deposits.—All the primary deposits of manganese are composed of carbonates and silicates, though small quantities are present in numerous other minerals. These carbonates and silicates were formed by solutions in the intermediate vein zone, where they are commonly associated with copper, zinc, and silver minerals. Subsequent alteration of these complex deposits gives rise to zinc- or silver-bearing manganese ores.

At the earth's surface, the oxides are the stable forms of manganese; and, therefore, wherever a deposit of the carbonate or silicate is exposed at the surface, it is soon converted into a residual deposit of the oxides. It is believed that all the manganese oxides are precipitated as colloids; some of them, as psilomelane and wad, remain colloids and therefore are amorphous; others crystallize. The presence of barium and potash in psilomelane is probably due to their absorption by the colloidal manganese oxide. The formation of stable colloidal minerals of manganese is another point in the similarity of manganese and iron. The residual deposits may accumulate on the surface over the original source of the manganese, or they may be mixed with clay at the surface. In either case, the ores are lateritic in type. They may, however, extend down as far as oxidation has progressed, which in some deposits is several hundred feet. Leaching of associated minerals and slumping concentrate them still further.

Manganese, which is slightly more soluble than iron, may be transported as the carbonate or sulfate. Where oxidizing conditions are

encountered by the solutions, the oxides are deposited. It is by this means that residual masses of ore are formed in clays at varying distances from the source of the manganese. Where conditions make it possible, the manganese is carried to a bog, lake, or bay and deposited, in this way giving rise to sedimentary beds of manganese.

A deposit of manganese minerals, on undergoing regional metamorphism, may be altered into a group of entirely different minerals. The "gondite" ores of India are evidently regionally metamorphosed sedimentary ores. Various methods of origin have been ascribed to the zinc, manganese, and iron ores of Franklin, New Jersey, but their mineralogy is best explained by regarding them as regionally metamorphosed deposits. According to this theory, the ores, which were originally replacement deposits in limestone, were oxidized and, later, deeply buried, whereupon the oxidized minerals were dehydrated and decarbonated and the present group of minerals (franklinite, zincite, and willemite) formed. This is discussed more fully as a zinc deposit (p. 214).

Manganese Deposits. *Domestic Deposits.*—The U. S. Geological Survey has data on 1,850 manganese deposits scattered through 32 different states, but the great majority of them are of little value.¹

The leading state in the production of manganese in 1928 was *Montana*. The most important deposits of this state are veins that furnish ore containing over 35 per cent manganese. They are located at Butte (Emma mine) and Philipsburg. Other states that produced high-grade ore in 1928 were (in order of production) Georgia, Arkansas, Arizona, Virginia, and New Mexico. States producing ore containing from 10 to 35 per cent manganese were New Mexico, Colorado, Michigan, Arkansas, and Georgia. Minnesota produced manganiferous iron ores in large quantities. The location of producing manganese deposits in the United States is shown on the map of Fig. 50. During 1928, a sedimentary deposit of manganese that occurs in the Pierre shales of the Cretaceous was found along the Missouri River near Chamberlin, South Dakota. It is low-grade ore but may prove to be a fair source of manganese.

Foreign Deposits.—The foreign deposits of manganese are much richer and larger than those of the United States (Fig. 51). *Russia* contains the greatest in the world. The very large reserves of the *Georgian Republic* are located at *Tchiaturi* in the province of *Kutais*. They are sedimentary deposits of pyrolusite, psilomelane, and wad. The ore bed, which is flat, ranges in thickness from 3 to 8 feet and covers 22 square miles. Estimates of the reserves of this field range from 22,000,000 to 200,000,000 tons of ore. American interests have a 20-year lease on these deposits. Another large manganese deposit is located at *Nikopol* in

¹ See *U. S. Mineral Resources*, 1918, Part 1, plate 5, p. 646.

Ukraine, to the north of the Black Sea. These reserves are largely under German control.

India has very large reserves of excellent manganese ore. They are in the central provinces. *Brazil* has many manganese deposits, but most of the production comes from the Lafayette district in Minas Geræs and the Nazareth district of Bahia. The other important deposit of manganese is that of the Dagwin mine, *Gold Coast, Africa*. These four countries (including the Georgian Republic with Russia) easily supply the world's demands for manganese. Smaller deposits occur in many other countries.

Uses of Manganese. *In Making Steel.*—The chief use of manganese is in the manufacture of steel; 14 pounds of manganese (metal) goes into every ton of steel produced. It requires 40 pounds of the average manganese ore to obtain the 14 pounds of manganese. According to the U. S. Bureau of Mines, the United States produced 51,544,180 long tons of steel in 1928; hence, about 722,000,000 pounds of manganese was used in its production. Of the manganese ores used in the United States, 92 per cent goes into steel; the other 8 per cent has various chemical uses.

Most of the manganese ore is used in making the alloy *ferromanganese*, and for this purpose the ores must have at least 46 per cent manganese and less than 6 per cent iron. Standard ferromanganese contains 78 to 82 per cent manganese, 8 to 15 per cent iron, 0.5 to 1 per cent silicon, 5 to 7 per cent carbon, some phosphorus, and traces of sulfur. Ferromanganese is used in making open-hearth steel.

A lower-grade alloy, *spiegeleisen*, which is made from the ferruginous manganese ore, contains 18 to 22 per cent manganese, 70 to 80 per cent iron, and 5 to 6 per cent carbon. It is used in making bessemer steel having a high-carbon content.

These alloys (principally ferromanganese) have a double function in the manufacture of steel. First, they aid in removing oxygen and sulfur by uniting with them and passing into the slag; and, second, they add the proper amount of carbon and manganese to the steel. Manganese gives added strength and hardness to steel and makes it easier to roll and forge.

Uses of Manganese Steel.—Structural steel, bridge steel, sheets, bars, and wire are composed of these high-manganese, low-carbon steels. For armor plate and armor-piercing projectiles, only very high-grade manganese steels are used. Manganese steel is widely used for making car wheels, rails, burglar-proof safes, ore chutes and screens, teeth for steam shovels, ore crushers and grinding machinery, plowshares, cultivator fingers, shovels, rakes, forks, cogwheels, car couplings, and many other articles.

Manganese is alloyed with numerous other metals, such as silicon, aluminum, copper, and magnesium.

Chemical Uses of Manganese.—The chemical uses of manganese are varied, but most of them are based on the *oxidizing* properties of the manganese minerals or compounds. Pyrolusite is the mineral best suited for most of these. About 80 or 85 per cent of the manganese ore used chemically at present (1928) goes into the manufacture of dry cells. This is due to the magnitude of the radio business. The use of manganese compounds in manufacturing chlorine and bromine is important, and other uses based on oxidizing properties are in the manufacture of wet cells, as disinfectants, as decolorizers in glass making, and as dryers in paints and varnishes.

Uses are made of manganese as a *coloring material* in the manufacture of glass, pottery, and brick; for printing and dyeing in the manufacture of cloths; and as pigments in paints.

Production of Manganese.—The production of high-grade manganese ore in 1928 in the United States was 46,636 long tons and the imports were 427,708 long tons. Montana leads, producing over half of the total production of the country.

The four countries which led in the importation of manganese ore into the United States in 1928 are shown in the following table:

TABLE 18.—AMOUNT AND VALUE OF THE MANGANESE ORE IMPORTED INTO THE UNITED STATES IN 1928 BY THE COUNTRIES LEADING IN ITS PRODUCTION¹

Country from which imported	Percentage of world's production each country produced in 1925	Amount of ore imported, long tons	Manganese content, long tons	Value
Russia (in Europe).....	29	159,842	79,529	\$3,067,259
Brazil.....	12	142,300	64,290	819,615
India (British).....	31	83,600	43,072	1,037,942
Gold Coast, Africa.....	13	24,186	11,712	145,059
Total.....	..	409,928		

¹ U. S. Bur. Mines, 1928.

Imports from all other countries amounted to only 17,780 long tons of ore.

The various low-grade manganese ores find their way into the market and are used in making numerous alloys. These ores include mangani-ferous iron ores, manganiferous-zinc residues, and ferruginous manganese ores.

Selected Readings on Manganese

CLARKE, F. W.: Manganese Ores, Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, pp. 539-542, 1924.

HARDER, E. C.: Manganese Deposits of the United States, U. S. Geol. Survey *Bull.* 427, 1910.

HEWETT, D. F.: Manganese, Spurr's "Pol. and Com. Geol.," pp. 90-108, 1920.
Good for survey of world's deposits of manganese.

PARDEE, J. T.: Deposits of Manganese Ore in Montana, Utah, Oregon, and Washington, U. S. Geol. Survey Bull. 725, pp. 141-243, 1922.

The annual volumes of *U. S. Mineral Resources* and *Mineral Industry* contain much information about manganese and have figures for production.

MOLYBDENUM

Molybdenum is an important constituent of certain alloys; and in the production of steels it can be substituted for other metals, especially tungsten and vanadium. Considerable difficulty has been encountered in the metallurgical treatment of the alloys containing molybdenum. These difficulties are being overcome, however, so molybdenum will take its place as a very important alloy metal.

Mineralogy.—Molybdenum occurs principally as *molybdenite*, MoS_2 (Mo = 60 per cent). Two other molybdenum minerals are fairly common, especially in the southwestern part of the United States. These are *wulfenite*, PbMoO_4 (MoO_3 = 39.3 per cent), and *molybdate*, MoO_3 .

Mode of Occurrence of Molybdenum Ores.—Molybdenite, the chief ore mineral, occurs as scattered grains and flat crystals in pegmatite veins, quartz veins, cracks and joints in granites and porphyries, and in contact-metamorphic deposits. Wulfenite and molybdate occur in the oxidized portions of the ore bodies. The deposits are of low grade, only rarely containing from 2 to 8 per cent molybdenum sulfide and usually less than 1 per cent.

Origin of Molybdenum Ores.—The mode of occurrence of molybdenite reveals its origin, as all the various types of deposits in which it occurs are formed by deposition from magmatic solutions. The wulfenite and molybdate are, of course, formed by the oxidation of the sulfide ores.

Deposits of Molybdenum in the United States.—Numerous molybdenum deposits occur in all parts of the United States, but practically all of the 1927 production came from Colorado and New Mexico. Some of the deposits in these states are among the largest in the world. The location of all of them is shown on the map of Fig. 50.

The deposit at Climax, Summit County, Colorado (about 15 miles northeast of Leadville), is one of the largest molybdenum deposits in the world and is the largest in the United States. The primary ore is molybdenite, which is disseminated through a highly brecciated quartz porphyry. The upper part of the ore body has been oxidized to molybdate. About 25 per cent of the ore occurs as molybdate, and it is hard to save. The company has blocked out between 20,000,000 and 25,000,000 tons of the ore carrying 0.9 per cent molybdenum sulfide. Another deposit in Colorado is at Empire, Clear Creek County, where

the molybdenite occurs in veins in a brecciated porphyry and, as in the Climax deposit, is a low-grade ore.

At Sulfur Gulch (7 miles east of Questa), Taos County, *New Mexico*, molybdenite occurs as well-defined veins associated with faulted zones in igneous rocks. The ore is higher in grade than that of the Colorado deposits.

A molybdenum deposit of some promise is found in the Leviathan mine (30 miles southeast of Yucca) in the Hualpai Mountains, Mohave County, *Arizona*. The ore is molybdenite and chalcopyrite in a quartz vein that cuts granite. It is said to average 2.5 per cent molybdenum sulfide.

Other molybdenum deposits are 10 miles west of Tonasket, Okanogan County, *Washington*; at Helvetia, Pima County, *Arizona*; at Mammoth, Pinal County, *Arizona* (ore mineral chiefly wulfenite); and (several) in *Maine*.

Chief Foreign Molybdenum Deposits.—Important foreign molybdenum deposits are those of the Knaben mine near Stavanger, *Norway*; those at Lake Malartic, Amos, *Quebec*; and those of Queensland and New South Wales, *Australia* (see map, Fig. 51).

Uses of Molybdenum.—Molybdenum has several important uses. It can be substituted for tungsten in making high-speed tool steels. One part can take the place of 2 or 3 parts of tungsten, though ordinarily only 0.25 to 0.40 per cent of molybdenum is used. This substitution greatly increases the toughness of the steel without affecting its ductility. Small quantities of molybdenum greatly increase the tensile and torsional strength and the elasticity of steel.

It has been difficult to control the introduction of molybdenum during the process of making steel, but an improvement in the method was made in 1927. Calcium molybdate or a compound called "calcium-silico-molybdate" is now added to the bath in the furnace, and the molybdenum from these compounds is absorbed into the steel. This method has replaced the old way of introducing the molybdenum as the powder or as ferromolybdenum.

Molybdenum is employed in producing cast iron, which it improves for many uses. Besides its alloy with iron, it forms one with chromium and iron; another with chromium, nickel, and iron; and another with nickel.

Molybdenum wire is used in electrical-resistance apparatus. Molybdenum has been substituted for platinum and iridium in electrical contact-making devices. The metal is employed in incandescent lamps to support the tungsten filaments.

Several molybdenum compounds are used in various industries. Ammonium molybdate is used to determine the amount of phosphorus

in iron and steel. Certain colors are produced by molybdenum compounds, especially in dyeing leathers.

Production of Molybdenum.—The production of molybdenum in the United States is large; in fact, this country probably could supply the needs of the entire world. The production in 1927 was 2,286,075 pounds of molybdenum, valued at \$1,858,786. That of Norway, the next most important producer, was far behind that of the United States.

Selected Readings on Molybdenum

HESS, F. L.: Annual volumes of *U. S. Mineral Resources*. One of the best sources of information.

MOORE, R. B.: Molybdenum, "Pol. and Com. Geol.," pp. 191–200, McGraw Hill Book Company, Inc., 1920. Good account of world's molybdenum deposits.

NICKEL

Nickel is the most important of the alloy metals, a statement which is not contradictory to the one made about manganese; for the indispensability of manganese is due to its function in the process of steel making. Nickel is used dominantly in nickel steel and other alloys. An interesting thing about it is that it occurs, in important quantities, in only two localities in the world, *i.e.*, Canada and New Caledonia.

Mineralogy.—Nickel occurs in two common mineral groups: (1) sulfides and arsenides and (2) silicates. The principal nickel sulfide is pentlandite, which in the important sulfide deposits is found in the ferrous sulfide pyrrhotite. Genthite is the other important nickel ore mineral. The common nickel minerals are given in the table below:

TABLE 19.—NICKEL MINERALS

Mineral	Composition	Percentage of nickel
Pentlandite.....	(Fe, Ni)S	22.00
Millerite.....	NiS	64.70
Nickelite.....	NiAs	43.90
Linnaeite.....	(CoNi) ₃ S ₄	3.00 to 20.00
Genthite.....	H ₄ Mg ₂ Ni ₂ (SiO ₄) ₃ ·4H ₂ O	10.00 to 32.00

Mode of Occurrence of Nickel Ores.—In the most important deposits of nickel known, those of Sudbury, Ontario, the nickel ore occurs at the bottom of a basic igneous rock, a norite, which is a variety of gabbro (see Fig. 53). The sulfides occur as a cementing material in a brecciated country rock, though some ore occurs also in other rocks. Similar occurrences of nickel sulfides exist in other regions, but the deposits are very small.

The other important nickel deposit, the New Caledonian, is a marked contrast to the Sudbury ores. In New Caledonia, the nickel occurs as

the hydrous magnesium nickel silicate in a residual deposit over serpentine.

Nickel minerals occur also in nickel-cobalt-copper deposits and in association with silver-cobalt ores, but none of these deposits is an important source of nickel.

Origin of Nickel Deposits.—In discussing the origin of nickel deposits, it is important that the character of the primary ores be considered, because it is the primary ore and its associated rock that furnish the needed evidence as to origin. Nickel in small quantities occurs characteristically in magnesian igneous rocks, usually in the mineral olivine. A large number of the smaller deposits are in such olivine-rich rocks or their common alteration product serpentine. This intimate association



FIG. 53.—Nickel-copper ores at the bottom of a basic igneous rock at Sudbury, Ontario. (Coleman, *The Nickel Industry*, Canada Dept. Mines Mon. 170, p. 34, 1913.)

between olivine and the nickel minerals clearly proves that such nickel deposits are of magmatic origin. It is quite probable that the peridotitic zone is very rich in nickel.

The nickel in the Sudbury deposits and several of the cobalt-nickel vein and lode deposits occurs as a sulfide unassociated with olivine, though in the Sudbury area the country rock is fairly rich in magnesium minerals. The Sudbury sulfide deposits illustrate the other common association of nickel, *i.e.*, with iron; and they indicate, also, the probable relationship existing in the interior of the earth, in both the metallic center and the sulfide zone above it. The Sudbury ores are regarded by some men as representing typical magmatic segregations. These men think that the heavy sulfides, insoluble in the silicate magma, sank to the bottom of the thick igneous mass. Others maintain that the ores were introduced into the rocks by hot solutions. The origin as a

magmatic segregation is the more probable solution, although a second period of mineralization may have been superimposed upon the first.

The oxidized nickel ores of New Caledonia; Riddles, Oregon; and other localities are the result of weathering. During this process, the nickel of the original mineral united with the magnesium of the serpentine to form the nickel-magnesium silicate genthite. Such ores are residual.

Nickel Deposits.—The nickel deposit of *Ontario* is in the county of Sudbury just north of Georgian Bay on Lake Huron (see Fig. 51). The deposit occurs at the base of the nickel eruptive (Fig. 53); and, as the general structure of the region is that of a syncline (35 miles long and 15 miles wide) striking northeast and southwest, the ores are found on the northwestern and southeastern sides. The igneous rocks form a great sheet nearly 6,000 feet thick. The ore has a fairly sharp contact with the wall rock. The chief sulfides are pyrrhotite, *pentlandite* (occurs in the pyrrhotite), and chalcopyrite. The ores usually contain about twice as much nickel as copper, and both are saved. The nickel content averages between 3 and 4 per cent but may be higher. A very large and rich new ore body has been found at a depth of 3,000 feet in the Frood mine. It is estimated to contain 100,000,000 tons of ore running 4 per cent nickel and 17 per cent copper.

The Sudbury ores contain precious metals, as is shown by the following table:

TABLE 20.—PRECIOUS METALS OBTAINED IN 1927 FROM THE NICKEL-COPPER DEPOSIT AT SUDBURY, CANADA¹

Metal	Amount, ounces	Value
Gold.....	4,866	\$ 99,900
Silver.....	188,180	105,759
Total gold and silver.....	193,046	197,659
Platinum.....	11,217	716,653
Palladium.....	11,247	541,319
Rhodium, ruthenium, osmium, and iridium....	298	12,871
Total platinum minerals.....	22,762	1,270,843

¹ U. S. Mineral Resources, 1927, Part 1, p. 405.

The recovery of 7.4 tons of precious metals (worth \$1,467,510) of which 0.74 ton belongs to the platinum group is especially interesting. The Sudbury deposits are apparently very large and will be able to supply the world with nickel for years to come.

The deposits of *New Caledonia* (Fig. 51) occur in various parts of the island; the largest mine is at the northwest end. The ores are all residual deposits of *genthite* occurring over serpentine. They are worked from

open pits, which extend down as far as the rock is altered, *i.e.*, about 35 feet. The ore averages 7 per cent nickel, as mined, and about 9 per cent after drying. The nearness of the Canadian deposits to the markets has curtailed the New Caledonian production. Somewhat similar (but smaller) nickel deposits occur in *Greece*, where some production is made. Similar nickel-silicate deposits occur at Riddles, Douglas County, *Oregon* (Fig. 50), but they are not worked.

A small deposit of *nickel-cobalt-copper ore* occurs near Fredericktown, Madison County, Missouri (Fig. 50). The ore body lies at the base of a dolomite and consists of massive iron sulfides, linnæite (a cobalt sulfide that contains from 3 to 20 per cent nickel), and chalcopyrite. The deposits have been worked but are not being worked at present (1929).

Uses of Nickel.—The chief use of nickel is as an alloy with iron and chromium. It is alloyed also with other metals. Nickel steels contain from 2 to 45 per cent nickel, though the great majority of them contain only from 2 to 4 per cent. Nickel steels possess great hardness, strength, and elasticity. Formerly, they were used dominantly for armor plate, gun turrets, projectiles, and other materials of war. The uses to which nickel was put in the United States in 1925 were as follows:

TABLE 21.—USES OF NICKEL IN UNITED STATES IN 1925¹

Used in production of	Percentage
Nickel steel (little of which was armor-plate steel) . .	37.00
White metals (German silver)	17.00
Anodes	23.00
Miscellaneous (including special alloys)	23.00
Total	100.00

¹ *U. S. Mineral Resources*, 1925, Part 1, p. 608.

Nickel-chromium steel is extensively manufactured. Monel metal contains about 67 per cent nickel; 28 per cent copper; and 5 per cent manganese, iron, and impurities. It has a high tensile strength and great resistance to corrosion. Ship propellers are made of it. Steels with 25 to 30 per cent of nickel are resistant to corrosion and are non-magnetic. White metals are made by alloying nickel, copper, and zinc in varying proportions. Lead, tin, and iron may be added to their composition. Our 5-cent piece is made of an alloy of nickel and copper. Nickel is extensively employed for plating purposes, but chromium will probably displace it in this use. Wires so fine that they are invisible to the naked eye can be drawn from a nickel-copper alloy. They are used for vacuum thermocouples. Due to possessing an almost negligible coefficient of expansion, nickel-iron alloys are used in making accurate tapes, pendulums, watch springs, and other instruments of precision.

Production of Nickel.—The only nickel produced in the United States is obtained from the refining of copper, though about 3,000 tons of secondary nickel is recovered annually. The remainder of the nickel used is imported, largely from Canada. In 1927, Canada produced 35,945; New Caledonia, 3,410; and the United States, 780 metric tons.

Selected Readings on Nickel

- COLEMAN, A. P.: The Nickel Industry, Canada Dept. Mines *Mon.* 170, 1913.
CORBETT, C. S.: Nickel, Spurr's "Pol. and Com. Geol.," pp. 129-141, 1920.
MILLER and KNIGHT: Nickel Deposits of the World, Royal Ontario Nickel Commission, Toronto, 1917.
RASTALL, R. H.: "The Geology of the Metalliferous Deposits," pp. 362-376, Cambridge University Press, 1923.

TITANIUM

Titanium ranks ninth in abundance among the elements composing the igneous rocks of the earth's crust. The estimated percentage is 0.63. The metal is of interest chiefly because of its use in steel alloys; and the oxide, because of its use as a pigment. In recent years, the demand for titanium as a pigment has exceeded its demand for alloy purposes.

Mineralogy.—The mineralogy of titanium is simple. *Rutile*, TiO_2 , is probably the most common of the titanium minerals. It is hard and insoluble and, as a result, is commonly found in sands and clays. *Ilmenite*, FeTiO_3 , forms in the basic rocks that are rich in iron. Where calcium and silica are abundant, *titanite*, CaTiSiO_5 , forms. All these minerals are resistant to weathering agents.

Mode of Occurrence of Titanium Minerals.—The titanium minerals occur in small quantities as accessory minerals in all types of rocks: igneous, sedimentary, and metamorphic. Rarely, these minerals may be concentrated into ore deposits. Rutile and ilmenite occur in workable deposits in dikes and associated igneous rocks. Apatite is an associated mineral in these deposits. Ilmenite also occurs in titaniferous-magnetite ores and as a concentrate in beach sands.

Origin of Titanium Deposits.—In such deposits as dikes, the rutile and ilmenite were deposited, of course, by magmatic solutions; and, where the minerals occur in the rocks surrounding the dikes, they are replacement, disseminated ores. In the titaniferous-magnetite deposits, the ilmenite is undoubtedly due to magmatic segregation. That of beach sands is, of course, a residual concentration, whatever its primary origin.

Deposits of Titanium Minerals.—Though titanium minerals occur in a great many localities in the United States (Fig. 50), only the deposits in Nelson County, Virginia; the beach-sand deposits at Pablo Beach, Duval and St. Johns counties, Florida; and deposits at Redondo, Los

Angeles County, California, are worked. The demand is increasing, and therefore other deposits may be opened in the future.

In Nelson County, *Virginia*, a dike of rutile, ilmenite, and apatite occurs in a syenite containing these three minerals. The deposit in the dike has been worked out; but, as the syenite contains from 3 to 6 per cent of rutile and the same of ilmenite, it is now being worked.

At Pablo Beach, *Florida*, ilmenite is being recovered by concentrating it from beach sands. These sands produce zirconium minerals, also. The *California* deposits are similar.

Other countries (Fig. 51) that produce titanium minerals are *Norway*, *India*, *Senegal* (Africa), *Brazil*, *Canada*, and *Portugal*.

Uses of Titanium.—The important uses of titanium are as the *alloy ferrotitanium*, as a *pigment*, and in *chemicals*.

Ferrotitanium—The ferrotitanium is used largely as a deoxidizer in the manufacture of steel, a use similar to that made of manganese and ferrosilicon. Ferrotitanium contains 17 per cent titanium and 7.5 per cent carbon. From 1 to 4 pounds of the alloy is used in producing a ton of steel. Larger amounts of it give an oxygen-free steel. Any nitrogen present also unites with the titanium. The presence of titanium makes a steel more malleable; hence, the use of titanium steel for rails. Titanium is also employed in certain copper alloys.

As a Pigment.—It has recently been found that, due to its high index of refraction, titanium oxide produces a pigment of great opacity. According to Ladoo, titanium oxide pigment is twice as opaque as zinc oxide and three times as opaque as white lead. The superior quality (*i.e.*, opacity) of the titanium oxide pigment is, moreover, not changed with the addition of less opaque materials, so long as a 25-per cent content of titanium oxide is maintained (see p. 525, under Paints).

Chemicals.—Titanium is used in coloring glass; in glazes and enamels for pottery; for tinting artificial teeth; and, in the form of various chemicals, for dyeing leather and cloth. Titanium tetrachloride, $TiCl_4$, is the chemical used in making smoke screens. The liquid titanium tetrachloride, when liberated, becomes a gas and takes up water from the air to form the dense white fumes of titanium hydroxide and hydrochloric acid. The addition of ammonia increases the density of the fumes. Titanium oxide is used in electrodes for arc lamps.

Production of Titanium Minerals.—Production figures for rutile in the United States in 1927 are unknown; the production of ilmenite that year was 3,500 tons, valued at \$44,000. Some ferrotitanium and titanium chemicals were imported, but the amount is unknown.

Selected Readings on Titanium

LADOO, R. B.: 'Non-Metallic Minerals,' pp. 629-637, McGraw-Hill Book Company, Inc., New York, 1925.

MARDEN, J. W.: Titanium, *Mineral Industry*, pp. 675-679, 1926.

WATSON, T. L.: Rutile Deposits of Virginia, U. S. Geol. Survey *Bull.* 430, pp. 200-213.

The list of uses is good.

TUNGSTEN

Few metals have a more fascinating story of the development of their uses than tungsten. It was discovered in 1791, but 115 years passed before the use (in incandescent lamps) to which it is the best adapted of any known substance was discovered. F. L. Hess,¹ of the U. S. Geological Survey, states: "The importance of tungsten among the metals in our type of civilization is comparable with that of lead and zinc and is exceeded only by that of iron and copper." The use of tungsten in incandescent lamps and in high-speed tool steel probably means a saving to the people of the United States of \$2,500,000,000 to \$3,000,000,000 annually.

Mineralogy.—Tungsten occurs in three minerals of economic importance. They are *wolframite*, $(\text{Fe}, \text{Mn})\text{WO}_4$; *scheelite*, CaWO_4 ; and *ferberite*, $\text{Fe}(\text{Mn})\text{WO}_4$. A fourth mineral, *hubnerite*, $\text{Mn}(\text{Fe})\text{WO}_4$, occurs in small amounts in some deposits. The amount of iron and manganese is variable in the three minerals containing them. Wolframite is world-wide in its distribution and is the chief source of tungsten.

Mode of Occurrence of Tungsten Minerals.—Wolframite is of common occurrence in pegmatites and high-temperature veins, where it is commonly associated with tin. Ferberite and scheelite occur in veins of the intermediate zone, but the latter appears, also, in contact-metamorphic deposits in limestone. Because of the insolubility and high specific gravity of these minerals, they are found in residual placer deposits; in fact, placers are the chief source of tungsten. The minerals associated with the tungsten minerals are those typical of the various types of deposits in which the latter occur.

Origin of the Tungsten Minerals.—All the tungsten minerals were formed under considerable pressure and at high temperatures. They were deposited by magmatic solutions most of which were rich in fluorine, for fluorite is a common gangue mineral. The placer deposits were formed, of course, by the weathering of some of the tungsten veins or other deposits.

Deposits of Tungsten Ores.—Tungsten minerals are of widespread occurrence, but few deposits are rich enough to mine. No less than 37 countries have, nevertheless, produced some tungsten ore during the last 10 years. China, Burma and the Shan States, and the United States are the only countries, however, whose annual production was more than 1,000 metric tons of an ore containing 60 per cent of WO_3 .

Domestic Deposits.—The only locality in the world where *ferberite* is mined is in southeastern Boulder County, Colorado (Fig. 50). It occurs

¹ HESS, F. L., Tungsten, *U. S. Mineral Resources*, 1927, Part 1, p. 435.

in a vein that was developed in a shattered zone in pre-Cambrian granite and gneiss. Quartz is the chief gangue mineral.

The United States is the only country where important deposits of *scheelite* occur. It is found at Atolia, Kern County, *California*, where it is present in a shattered gold-quartz vein in a granodiorite. Placer deposits of scheelite are also worked in this region. Scheelite deposits of a contact-metamorphic character occur at Bishop, Inyo County, *California*; and at Toy, Humbolt County, *Nevada*.

Wolframite is mined at Lead, *South Dakota*, in the northern part of the Black Hills. It occurs in irregular replacement veins. Deposits have been worked in the Dragoon Mountains, Cochise County; at Oracle, Pinal County; and at Arivaca, Pima County, *Arizona*. Small amounts occur in *Utah*, *Nevada*, and *Missouri*.

Foreign Deposits.—*China* furnishes most of the world's tungsten ores (Fig. 51). The deposits, which are placers, occur in southwestern Kiangsi and adjacent parts of Kwangtung and Hunan. *Burma* produces wolframite from tin deposits but cannot compete with China unless the price of the ore is over \$5 per short-ton unit (a short-ton unit is 20 pounds and a long-ton unit is 22.4 pounds of WO_3).

Uses of Tungsten.—It is difficult to say which of the two major uses of tungsten is the more important, that in incandescent lamps or that in high-speed tool steels.

In Incandescent Lamps.—Less than 100 tons of ore, carrying 60 per cent WO_3 , will supply the yearly needs of the United States for tungsten filaments in incandescent lamps. No other substance known can produce a lamp giving the quality of light attained by these or do it so cheaply. Tungsten filaments use about one-third as much electricity as the old carbon filament. The saving thereby in this country in 1927 was estimated at more than \$2,000,000,000. It is of interest to note that in 1926 (20 years after the first use of tungsten in lamps), 294,000,000 large tungsten-filament lamps were sold in the United States, and, in addition, 188,340,000 miniature lamps, Christmas-tree lamps, flash-light lamps, automobile lamps (116,300,000 of these), and miscellaneous types. The Christmas-tree lamps were equal to 6,000,000 40-watt lamps.

Tungsten wires, 0.0002 inch in diameter, can be drawn in quantity. These wires are practically invisible to the naked eye, and it would require 100 of them to make a wire the size of a human hair.

In Making Steel.—The high-speed tool steels, in the construction of which tungsten is so necessary, are hard and hold a cutting edge a long time. The use of tungsten enables a cutting machine to be run at five times the speed possible with a carbon-steel tool. One man using a tungsten-steel tool can do the work of five men using carbon-steel tools. Carbon steel loses its temper at 500°C., whereas tungsten steel cuts at 1,100 to 1,200°C.; and the chips, as they come off the piece being

turned, drilled, or planed are red hot. The saving from using tungsten steel is thus enormous. One automobile manufacturer estimated a \$200 saving on the construction of each car. Hess estimates that even if only \$50 were saved in making each automobile, it would amount to over \$200,000,000 a year in the United States, and this estimate does not take into account the additional amount of machinery that would be necessary in constructing the automobiles under the old method. Very probably, the total saving in all the industrial plants in the country where tool steel is used amounts to a billion or a billion and a half dollars per year. The average tungsten tool steel, moreover, contains only 15 to 20 per cent of tungsten; and about 3,450 tons of tungsten ore containing 60 per cent WO_3 supplies the yearly needs of the United States.

Other high-speed steels are made, but none is so easy to make as tungsten steel. The following table gives an analysis of an average tungsten steel:

TABLE 22.—COMPOSITION OF AVERAGE TUNGSTEN STEEL¹

Constituent	Percentage
Tungsten.....	17.560
Chromium.....	3.660
Vanadium.....	1.060
Molybdenum.....	0.830
Carbon.....	0.670
Manganese.....	0.230
Silicon.....	0.060
Phosphorus.....	0.021
Sulfur.....	0.010
Iron (by difference).....	75.899
Total.....	100.000

¹ U. S. *Mineral Resources*, 1927, Part 1, p. 434.

About 20,000,000 pounds of high-speed tool steel is made annually in the United States. The different uses to which it is put, as outlined by H. E. Nichols, is shown in the following table:

TABLE 23.—DIVISION OF USES OF HIGH-SPEED TUNGSTEN STEEL¹

Use	Percentage
Twist drills, reamers, counterbores, and formed tools of this type.....	30.00
Cutter hobs, mills, and formed tools of this type.....	25.00
Disks, punches, etc.....	15.00
Turning tools, lathe, planer, shaper, boring tools, etc.....	20.00
Other uses.....	10.00
Total.....	100.00

¹ U. S. *Mineral Resources*, 1927, Part 1, p. 434.

Other Uses.—Other uses of tungsten are numerous though not so important. Tungsten (as calcium tungstate) is used in making X-ray

tubes, radio tubes, electrical contacts, airplane and automobile valves, phonograph needles, gold and bronze powders, permanent magnets, standard precision weights, and pens and knife blades. Tungsten has the highest melting point of any metal, *i.e.*, $3,080^{\circ}\text{C}.$, which is over $1,200^{\circ}\text{C}.$ higher than the melting point of platinum. It is used, therefore, instead of platinum for crucibles, in spark plugs, telegraph relays, and other articles. A tungsten carbide carboloy has recently been made, which has a hardness above 9 and is used in a cutting tool that cuts glass, bakelite, porcelain, manganese steel, and aluminum. Only a small piece of carboloy is brazed to the tool. It is regarded as the most important development in metal cutting since high-speed tool steels were invented. Drill bits used in boring for oil are also made from this alloy. It sells at

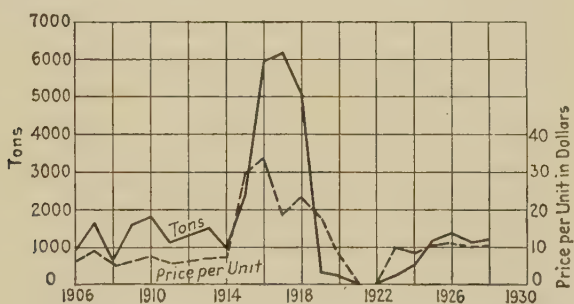


Fig. 54.—The production of tungsten ores (60 per cent WO_3) in the United States, showing the influence of high prices and war stimulation. (Data from U. S. Bur. Mines.)

\$200 to \$400 a pound. Sodium tungstate is used in fireproofing curtains and draperies. Some tungsten is used to color glass, and silks are weighted with it.

Production of Tungsten Ores in the United States.—Under the highest tariff the United States government imposes upon any raw material (a tariff without justification, for our deposits of tungsten are almost negligible), this country in 1927 produced 1,164 short tons of tungsten ores containing 60 per cent of WO_3 . At the average price of \$10.37 per unit, each ton was worth \$628.20. Figure 54 shows the effect of high prices on mining. Production began in 1923, only after the tariff was imposed in 1922.

The remainder of our needs for tungsten in 1927 was imported from China, as it has been since 1919.

Selected Readings on Tungsten

- HESS, F. L.: Tungsten, *U. S. Mineral Resources*, 1927, Part 1, pp. 423-440. Very good.
 — and LARSEN: Contact-metamorphic Tungsten Deposits of the United States, *U. S. Geol. Survey Bull.* 725, p. 245-309, 1922.

VANADIUM

Vanadium minerals are rare, but traces of the element are found in most rocks. Its amount in the earth's crust is estimated at 0.017 per cent, and it occurs most commonly in the basic igneous rocks. It is surprising to learn that vanadium is commonly found in organic remains. The ash of coal, asphaltum, and petroleum shows it; rarely, such a vanadium content is as high as 12 per cent. It is a constituent of the blood of the holothurians (sea cucumbers).

Mineralogy.—Most of the vanadium minerals are complex. The exact composition of some of them has not been worked out. The most important ore mineral is a complex sulfide, *patronite*, possibly having the formula VS_4 . Another important mineral is a vanadium mica, *roscoelite*, which is apparently a muscovite in which vanadium has replaced part of the aluminum. Roscoelite contains about 24 per cent of V_2O_3 . *Vanadinite* and *descloizite*, two lead-vanadium minerals (descloizite may also contain zinc and copper), are important sources of vanadium in a few areas. *Carnotite*, which is one of the important sources of radium, contains 18 per cent of V_2O_5 a part of which is saved as a by-product.

Mode of Occurrence of Vanadium Minerals.—Vanadium minerals are variable in their mode of occurrence. Roscoelite occurs mainly in sandstones; in some deposits, in connection with carnotite. Patronite is known only in the Peruvian deposits, where it occurs in a black carbonaceous substance resembling coal. The other vanadium minerals occur in the oxidized portions of veins and other types of deposits that contain vanadium.

Origin of Vanadium Deposits.—Vanadium ores have a threefold origin: some are *magmatic*; others are *secondary*; and still others, which are the most important, are apparently *organic*.

Deposits of *magmatic* origin include the titaniferous magnetites, the roscoelite deposits of the intermediate veins, and the insignificant quantities of vanadium in ferromagnesian minerals of basic igneous rocks. None of these is a workable vanadium deposit, though the element is saved as a by-product in working the magnetites.

The *secondary* deposits are the result of the concentration of the vanadium from various kinds of rocks into oxidized deposits, as those in sandstones. In most of these deposits, the immediate source of the vanadium is unknown.

The deposits of *organic* origin are represented by the patronite deposits of Peru. They were probably formed by organisms' concentrating the vanadium, although the evidence that has been worked out is not fully convincing.

Deposits of Vanadium. Domestic Deposits.—The only important sources of vanadium in the United States are in *southwestern Colorado*, *southeastern Utah*, and *northern Arizona* (see Fig. 50). The most impor-

tant areas of the region are near Rifle and New Castle, Garfield County; Placerville, San Miguel County; and in Montrose, Dolores, and Montezuma counties, Colorado. In Utah, the important areas are in Grand and San Juan counties. The deposits are scattered over a wide area of flat-lying Jurassic sandstones, in which the ore occurs as a cement. It is a low-grade ore, rarely exceeding a 3-per cent vanadium content. Minor deposits occur in *southern Arizona, New Mexico, and Nevada.*

Foreign Deposits.—Peru is the world's chief source of vanadium at present (Fig. 51). The deposit is located at Minasragra, province of Pasco. The chief ore mineral is patronite, occurring in a black carbonaceous rock. It contains from 10 to 13 per cent of vanadium. Most of this ore comes to the United States.

Other countries (see Fig. 51) that contain deposits of vanadium are *Southwest Africa Territory* (ranks next to Peru in production), *Mexico*, and *northern Rhodesia.*

Uses of Vanadium. *In Steel Alloys.*—The chief use of vanadium is in steel alloys, though it is also employed in making cast iron, brass, and bronze. It is alloyed with iron, and the ferrovanadium is used in making steel. During the process of steel making, the vanadium helps to remove oxygen and nitrogen. Usually, less than 1 per cent of vanadium is used in steel (0.2 per cent is common), though 1.5 per cent is employed in some.

Vanadium steels are very tough and resistant and thus are well suited for uses that involve strains. Such uses are in locomotive and automobile frames; transmission shafts; and large bearings, axles, and castings. The element gives other special properties to steel, properties which can also be produced, however, by nickel and molybdenum. Vanadium can be substituted for a part of the tungsten in tungsten high-speed steels.

Chemical Uses.—A new use of vanadium pentoxide, V_2O_5 , has recently been developed. This is as a catalytic agent, especially as a substitute for the very expensive platinum in making sulfuric acid. Vanadium has proved to be so efficient for this purpose that the prediction is that it will supplant platinum within the next 10 years (from 1928). Various vanadium compounds are employed in paints, in dyeing processes, in printing fabrics, and in medicines. Metallic vanadium has recently been produced by Marden and Rich¹ and may prove to have important uses.

Production of Vanadium.—The production of ferrovanadium in the United States in 1928 amounted to 2,019 long tons. The alloy had an average vanadium content of 37.42 per cent. The average value per

¹ MARDEN and RICH, *Vanadium, Ind. and Eng. Chem.*, vol. XIX, pp. 786-788, 1927.

pound of vanadium in this alloy was about \$3.20. The figures for the imports of the element in the United States in 1928 are not available, but, in 1927, 13,885,760 pounds of the ores, valued at \$561,041, was imported. All the production figures for 1927 are not available, but if the United States' production was equal to that in 1926 (and apparently it was larger), this country consumed in 1927 about 80 per cent of the world's production of vanadium. At the present rate, the world's reserves will last about 20 years.

MINOR ALLOYS

Several minor alloys might be mentioned, some of them ferro-alloys. *Ferrosilicon* is one of the most important of these. It contains over 7 per cent silicon and is used extensively in steel making. In 1928, the United States produced 310,770 long tons of ferrosilicon, valued at \$15,199,746. Only small amounts of the other minor alloys are used. These alloys are *ferrophosphorus*, *silicomanganese*, and *calcium-molybdenum*.

CHAPTER VI

COPPER

Copper is as indispensable in modern civilization as iron. Its physical properties, especially its efficient transmission of electrical energy, place it at the head of all metals for electrical and numerous other purposes. It is fortunate that copper is so widely distributed throughout the world. Workable deposits of it are even more common than those of iron.

History of Copper.—The early history of copper has been outlined under the discussion of the uses of the metals by ancient man (pp. 8-, 10). From this early period down to the beginning of the nineteenth century, copper was produced by many countries, though in small quantities. For the decade of 1801 to 1810, the average annual production of the world was only 18,200 tons.¹ The copper production, by decades from 1801 to 1925, of the leading producing countries of the world is shown in the following table:

TABLE 24. LEADING COPPER-PRODUCING COUNTRIES OF THE WORLD BY DECADES, 1801-1925¹

Decade	Percentage production		
	England	Chile	United States
1801-1810	40.00	9.23	
1811-1820	43.61	8.91	
1821-1830	45.06	11.06	
1831-1840	44.25	13.83	
1841-1850	31.34	19.98	0.54
1851-1860	20.99	31.66	5.46
1861-1870	11.33	43.56	9.46
1871-1880	3.83	36.08	14.66
1881-1890	1.02	16.14	32.33
1891-1900	0.16	6.27	51.92
1901-1910	0.08	4.76	56.13
1911-1920	0.02	6.20	58.75
1921-1925	0.01	14.00	52.44

¹ U. S. Bur. Mines *Econ. Paper* 1, 1927.

England, as seen from the table, produced the largest part of the world's copper from 1801 to 1850. Chile then assumed the lead and held it

¹ These and many other figures as to the production of foreign countries and of the world are quoted from the recent excellent U. S. Bur. Mines *Econ. Paper* 1, on Summarized Data of Copper Production, by C. E. Julihn and others of the staff.

for three decades, when it was passed to the United States (actually in 1883).

History of Copper in the United States.—As seen from the above table, the United States did not enter the list of copper-producing countries until during the decade of 1841 to 1850, though the colonists had begun the search for *all* metals as soon as they arrived in America.

Copper was discovered at Simsbury, Hartford County, Connecticut, very early in the eighteenth century, as a charter to mine it was secured from the British crown in 1702. Although the deposit was worked for several years, the production was small. The discovery of copper in New Jersey, about 15 miles northwest of New York City, occurred in 1719. This deposit, known as the "Schuyler mine," has been worked at various intervals since then, but its total output is small. The Gap mine in Lancaster County, Pennsylvania, was developed in 1732, but its history has been similar to that of the Schuyler mine. There was considerable excitement in New Jersey from 1748 to 1751 over finding native copper, but the excitement had little foundation. Whitney¹ is the authority for the statement that attempts were made to mine copper on Lake Superior in 1771. Records show that native copper was mined by the Spaniards about 1800 in what is now the Santa Rita district of southwestern New Mexico. A little of the metal was found with gold in North Carolina during the gold-mining period of 1800 to 1825. Copper was reported at Bristol, Connecticut, in 1836; in Missouri at Mine La Motte, Madison County, in 1838; and in the lead mines of southwestern Wisconsin in 1839.

It is a curious fact that the large metalliferous areas of the United States are west of the Appalachian Mountains; and, although exploration and settlement were being pushed westward all the time, few discoveries of ore deposits occurred before the first half of the nineteenth century. From 1841 to 1850 was the period of the first important discoveries. During this interval, the iron and copper deposits of the Lake Superior region and the gold deposits of California were discovered.

His discovery of the native copper deposits of the *Lake Superior region* was reported by Dr. Douglas Houghton (after whom Houghton, Michigan, was named) in 1841. Mining began in 1845; and, as the news of the discovery spread in the east, the supposed richness of the deposits caused a mad rush to the region and a speculative period during 1845 and 1846 (a typical occurrence when new discoveries of valuable mineral deposits are made). The bubble burst in 1847, and from that time the district grew rapidly, soon becoming one of the greatest copper-mining areas of the world. With mining firmly established in this region, the United States entered the list of the world's copper-producing countries.

¹ WHITNEY, J. D., "The Metallic Wealth of the United States," p. 247, 1854.

We cannot leave this bit of history about the Lake Superior deposits without calling attention to the fact that copper had been mined in the region long before Dr. Houghton discovered it. Numerous openings where mining had been done occur throughout the area. Some of the pits are 50 feet deep. These early miners used stone tools (rarely copper tools) and fire to remove the metal. Who they were is unknown, as the present Indians of the region have no traditions to account for them. Attempts have been made to connect the Aztecs with this mining, but there is little evidence to support the theory. A carved stone figure evidently of Mexican origin, found in northwestern Missouri a few years ago, is suggestive, but nothing more.

Copper was discovered at Ducktown, Tennessee, in 1847 and in California about the same time; but no other important discoveries were made until 1868, when the metal was found at Butte, Montana. The Arizona deposits were discovered in the seventies. Production did not begin at most of these western camps until the seventies and early eighties. Many of these important copper camps were worked for gold (usually placer gold), silver, and lead before they became copper camps. The development of the immense disseminated copper deposits (porphyry coppers) did not occur until after 1900, when methods of concentrating the low-grade ores had been devised. Since then, enormous reserves of this type of copper ore have been developed, and they now furnish a large part of the copper produced.

The great development of the mines in the western part of the United States occurred as soon as railroads had opened up the country. From a small beginning (112 tons) in 1845, the production rose so rapidly that in 28 years (in 1883) the United States had become the world's leading producer of copper. By the end of 1927, the United States had produced 48.43 per cent of the world's total production.

Abundance of Copper.—The detailed analysis of rocks has revealed that traces of copper are present in most rocks. The estimates as to the amount have a rather wide range. That by Clarke and Washington is 0.01 per cent of copper in the earth's crust, but this is probably too high. Other estimates are as low as 0.001 per cent and even lower. The copper minerals, usually as mere grains, are present in all sorts of rocks and mineral veins.

Mineralogy of Copper.—Copper occurs in several forms in the rocks. It may be combined with sulfur, carbon dioxide, or oxygen and may also occur uncombined as native copper. The most important minerals are the sulfides. The following table gives the composition and the percentage of copper of the principal copper ore minerals:

TABLE 25.—THE CHIEF COPPER MINERALS AND THEIR COMPOSITION

Name	Composition	Percentage of copper
Native copper.....	Cu	100.00
Cuprite.....	Cu ₂ O	88.80
Chalcocite.....	Cu ₂ S	79.80
Covellite.....	CuS	66.40
Bornite.....	Cu ₅ FeS ₄	63.30
Malachite.....	2CuO.CO ₂ .H ₂ O	57.40
Azurite.....	3CuO.2CO ₂ .H ₂ O	55.30
Enargite.....	Cu ₃ AsS ₄	48.30
Chrysocolla.....	CuO.SiO ₂ .H ₂ O	45.00
Chalcopyrite.....	CuFeS ₂	34.50

There are many other copper minerals besides the common ones shown in the table.

Physical Properties and Important Occurrences of the Copper Ore Minerals. *Native Copper.*—Copper is copper-red in color; has a hardness of 2.5; is ductile and malleable; and occurs in grains, crystals, sheets, and irregular masses. Much of it is coated with copper oxide or copper carbonate. Native copper is the dominant copper mineral in the Lake Superior district and is also found in Arizona and New Mexico.

Cuprite.—Cuprite is dark to brownish red. By transmitted light, the color is a deep red. Its hardness is 3.5 to 4, and it occurs as crystals and grained masses. Cuprite is not very common; the chief localities where it is found are Bisbee, Arizona; and Santa Rita, New Mexico.

Chalcocite.—Chalcocite is a dark lead-gray, but it tarnishes readily to black. Its hardness is 2.5, its streak is black, and it occurs in fine-grained masses. It is a very important source of copper and yields most of the copper production of the United States. Chalcocite is very abundant at Butte, Montana; Kennecott, Copper River district, Alaska; and in Utah; Arizona; and New Mexico.

Covellite.—Covellite is a deep indigo-blue. Its hardness is 1.5 to 2. It may occur as flat, six-sided crystals but usually is massive or occurs as incrustations on other minerals. It is fairly common at Butte, Montana.

Malachite and Azurite.—Both these minerals are readily distinguished by their color. Malachite is green and azurite blue. The former is the more common. Both are found in abundance in the copper mines of Arizona, New Mexico, and elsewhere.

Bornite.—Bornite is sometimes called "purple ore" or "horse-flesh ore" in allusion to its purple tarnish. A fresh surface is bronze to copper-red. Its hardness is 3, and it usually occurs massive. It is abundant at Butte, Montana.

Enargite.—Enargite is dark-gray to black, has a hardness of 3, and occurs as compact or columnar masses. It is common at Butte, Montana, and in the Tintic district, Utah.

Chalcopyrite.—Chalcopyrite has the most widespread occurrence of any of the copper minerals. It is brass-yellow (darker than pyrite) and usually has a blue, purple, black, or iridescent tarnish. Its hardness is 3.5 to 4. It occurs as crystals, massive, and as grains scattered through the rock. Chalcopyrite is found in most copper mines in the United States but most abundantly at Bingham Cañon, Utah; Bisbee, Arizona; Butte, Montana; and Ducktown, Tennessee.

Composition of Copper Deposits.—A copper deposit may consist of a single copper mineral, as the Lake Superior deposits containing only native copper, or it may be composed of several minerals. In the main, there are three classes of copper ores: (1) *native copper ores*; (2) *oxidized ores*, which consist of the carbonates malachite and azurite; the oxide cuprite, and less often native copper and some minor minerals; and (3) *sulfide ores*, which contain various combinations of chalcopyrite, chalcocite, covellite, bornite, and enargite. Each district has its own particular combination of minerals.

Secondary Enrichment of Copper Deposits.—Copper deposits are especially susceptible to enrichment, both *sulfide enrichment* and *oxidation*. As the oxidized deposits are close to the surface (Fig. 27, p. 74), they constituted the first ores mined in many districts, especially those of southwestern United States.

Oxidized Deposits.—The oxidized zone contains the two carbonates malachite and azurite and varying amounts of cuprite, native copper, and chrysocolla. The copper sulfates may form where there is a deficiency of water. They occur in the deposits at Chuquicamata, Chile. Deposits of oxidized minerals may be very rich, as were the early ores in the Bisbee district, Arizona, which ran from 20 to 25 per cent copper; or they may be of low grade but workable because large amounts of ore can be handled, as the deposits of Ajo district, Arizona, or of Santa Rita, New Mexico.

Sulfide Enrichment.—Sulfide enrichment occurs more commonly in copper deposits than in those of any other metal. The copper is taken into solution in the oxidizing portions of a deposit and carried down to the zone of sulfides below the water level. That carried down is deposited as a sulfide, usually chalcocite but also covellite. The enriched zone may be only a few feet thick, in which case the deposit is usually rich, or it may be many feet thick. The controlling factor in this is the kind and amount of the precipitating sulfide mineral present.

Gangue Minerals and Associated Ores of Copper Deposits.—Associated with the copper ore minerals are various gangue as well as other metal-bearing minerals. Common gangue minerals are *quartz*, *calcite*,

dolomite, barite, siderite, pyrite, iron oxides, and feldspars. Where the ore is in igneous rocks and contact-metamorphic deposits, numerous silicates occur as gangue minerals. *Galena* and *sphalerite* are common in some copper deposits, where they form a complex ore requiring special treatment. *Gold* and *silver* are almost always present in copper ores and are recovered during the electrolytic refining of the copper.

Types of Copper Ores.—Copper ores are variously designated on the basis of the metals found in the ores as copper ore, copper-lead ore, copper-zinc ore, siliceous copper ores, and siliceous copper-lead ores.

Copper Content of Copper Ores.—The copper content of the copper ores produced in the United States for the last 20 years and, also, the amount and value of the gold and silver they contained are shown in the following table:

TABLE 26.—COPPER ORES PRODUCED IN THE UNITED STATES, 1906-1927¹

Year	Copper production, short tons	Percentage of copper in ores	Amount of gold per ton of ore, ounces	Amount of silver per ton of ore, ounces	Value per ton of gold and silver
1906	18,000,000	2.50	0.0150	0.882	\$0.856
1907	20,253,000	2.11	0.0135	0.609	0.682
1908	22,290,886	2.07	0.0104	0.666	0.560
1909	27,932,618	1.98	0.0097	0.655	0.540
1910	28,497,238	1.88	0.0093	0.562	0.495
1911	29,988,235	1.82	0.0089	0.555	0.492
1912	35,656,414	1.71	0.0073	0.517	0.468
1913	36,336,682	1.67	0.0057	0.502	0.420
1914	35,171,541	1.60	0.0075	0.422	0.390
1915	43,404,182	1.66	0.0078	0.428	0.380
1916	57,863,365	1.70	0.0069	0.424	0.420
1917	58,482,694	1.60	0.0058	0.347	0.490
1918	62,289,069	1.50	0.0050	0.328	0.500
1919	36,121,622	1.65	0.0052	0.356	0.510
1920	36,765,370	1.63	0.0047	0.331	0.460
1921	13,396,382	1.70	0.0039	0.357	0.440
1922	26,893,247	1.74	0.0049	0.386	0.490
1923	45,519,317	1.58	0.0060	0.321	0.390
1924	49,178,315	1.59	0.0063	0.325	0.350
1925	53,103,014	1.54	0.0065	0.338	0.370
1926	57,181,894	1.46	0.0064	0.293	0.310
1927	56,725,460	1.41	0.0065	0.255	0.280

¹ U. S. Bur. Mines.

This table shows that the tenor (copper content) of the copper ores mined has been steadily decreasing. This is true also of the precious-metal content.

Copper ores are either sent directly to the smelter or first concentrated to increase the copper content. The copper content of these two types of ores differs, as is shown by the following table:

TABLE 27.—COPPER CONTENT OF THE SMELTING AND CONCENTRATING ORES PRODUCED IN THE UNITED STATES, 1918, 1919, 1924, 1926¹

Year	Smelting ores		Concentrating ores	
	Amount, short tons	Percentage of copper	Amount, short tons	Percentage of copper
1918	6,223,674	4.51	53,937,796	1.18
1919	3,465,880	4.64	30,769,966	1.35
1924	3,554,915	5.08	44,427,264	1.33
1926	3,767,947	4.75	52,083,784	1.24

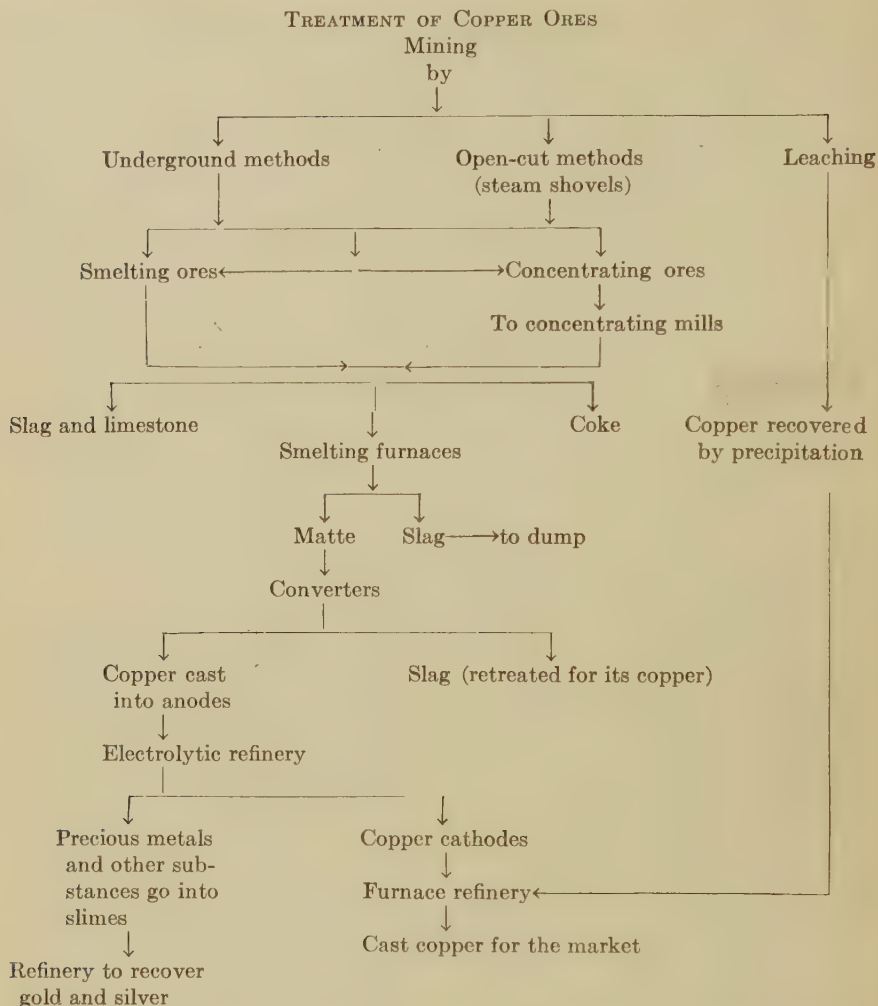
¹ *U. S. Mineral Resources.*

The great tonnages of concentrating ores produced come from the low-grade porphyry and other disseminated deposits.

It is astonishing how low may be the grade of ores that are worked. In Utah during 1926, a total of 13,880,100 tons of concentrating ores was treated, which averaged only 1.01 per cent copper, or 20.2 pounds per ton. At the average price of copper that year (\$0.14 per pound), the total value of the copper per ton of rock was \$2.828; and of the gold and silver, \$0.20. Due to losses during the treatment, however, only 17.58 pounds of the copper was recovered per ton; it was worth \$2.66. All the mining, concentrating, and smelting had to be done for this small sum per ton. The copper was actually produced for \$0.0794 per pound, and the company's net profits on the year's production were \$13,809,310. Only the large-scale methods of mining used and the efficient mill and metallurgical practice make such a situation possible. Other states show somewhat similar figures of production costs. The total production of over 52,000,000 tons of ore having only 1.24 per cent of copper tells its own story of the efficiency of copper production in the United States.

Impurities of Copper Ores.—Several substances occurring in copper ores are injurious to the usefulness of the metal. Zinc and silver should be removed. The presence of the latter lowers the copper's electrical conductivity. Sulfur makes it brittle when cold; phosphorus does the same when hot. Other injurious substances are arsenic, antimony, bismuth, and tellurium. All are reduced to a percentage as low as possible during the refining process.

Treatment of Copper Ores.—The treatment of copper ores comprises an interesting series of steps, which are represented graphically below:



Mining.—Mining of copper is carried on underground and on the surface in open cuts (Figs. 59 and 60, pp. 166, 168).

Many special adaptations of *underground-mining* methods have been made for the mining of low-grade ores. By these (many are called “caving methods”), large tonnages of ore are mined very cheaply. The amounts brought to the surface in 24 hours by the modern high-speed hoisting engines and self-dumping skips (a special type of bucket) are enormous. Ores of sufficiently high grade (the average smelting ore in 1926 contained 4.75 per cent copper) are sent directly to the smelter without further treatment; low-grade ores are first concentrated.

An example of one of the special underground-mining methods is the leaching method which has recently been successful. By this means,

water from the surface is introduced into the mines and allowed to percolate through the ores. The copper is removed from the ore as the copper sulfate, which is formed by the oxidation of the original sulfides by the oxygen of the water. The solution is then conducted through scrap iron, where the copper is precipitated as metallic copper (the iron going into solution as the sulfate).

The *open-cut methods of mining* are used where the ore body is near the surface. The overburden, or waste rock, is removed (Figs. 59 and 60), and the ore is then mined by steam shovel (many of 7-tons capacity). These shovels load it directly into railroad cars for hauling



FIG. 55.—The Arthur Concentrating Plant of the Utah Copper Company, on the south shore of Great Salt Lake, Utah. (Photograph furnished by the Utah Copper Company.)

to the concentrating mills. Ores containing less than 1 per cent of copper can be mined by these methods.

Concentration.—Most concentrating ores consist of minute grains of the copper sulfides scattered through the country rock. These must be separated and collected before further treatment can take place. The concentrating mills are of enormous capacity. Those of the Utah Copper Company (Fig. 55) handle from 20,000 to 25,000 tons of rock a day. The railroad cars are unloaded by turning them over, and the other machinery is designed to keep pace with this rapid method of unloading. The ore is crushed and ground fine, after which the sulfide grains are saved by floating them off with oil. These concentrates are dried and sent to the smelter.

Smelting.—At the smelter, the copper ore, limestone, and coke are put into blast furnaces. These are about 5 by 15 by 18 feet in size,

though other types are used, also. The charge of ore must contain certain amounts of copper and iron (usually, sufficient iron is present in the copper ore) and enough sulfur to unite with both metals. The various materials melt. The silica, lime, and some iron unite to form a slag; and the copper, iron, and sulfur unite to form what is called the "matte." Any gold, silver, or other impurities in the ore go into the matte. The matte and slag are drawn off from time to time. The latter is hauled to the dump, and the former is taken in 15-ton ladles to the converter.

The converters are barrel shaped. Some of those of the Anaconda Copper Mining Company are 20 feet in diameter, 17 feet high, and if lined weigh about 225 tons. The lining is of magnesite brick. A single charge for a converter consists of 75 tons of matte from the blast furnace and some siliceous flux. Air is blown through the matte until the iron sulfide has become oxidized and united with the silica to form a slag. This slag is poured off, and air is again blown through the charge until the sulfur of the copper sulfide is burned off, leaving the blister copper that also contains the gold and silver. This is poured into molds, where blocks of copper called "anodes" are formed. These anodes are 36.5 by 28 by 1.75 inches in size, and their approximate composition is represented in the following table:

TABLE 28.—APPROXIMATE COMPOSITION OF BLISTER COPPER AS IT COMES FROM THE CONVERTER¹

Constituent	Amount
Copper.....	99.3 per cent
Arsenic.....	0.3 per cent
Antimony.....	0.2 per cent
Iron, nickel, and miscellaneous.....	0.2 per cent
Silver.....	70.0 oz. per ton
Gold.....	0.4 oz. per ton

¹ Data from booklet published by the Anaconda Copper Mining Company.

Electrolytic Refining.—The copper anodes are taken to the electrolytic plant and placed in lead-lined tanks containing a dilute solution of sulfuric acid. Between each anode is placed a thin sheet of copper called the "cathode." An electric current is sent into the anode and is carried to the cathode by some of the copper's going into solution in the electrolyte. The dissolved copper is deposited on the cathode. It takes about 24 days for the anodes to go into solution, but the cathodes are removed after 6 to 14 days. When 12 to 15 per cent of the anode remains, it is removed. The gold and silver and other insoluble impurities sink to the bottom of the tank as a slime, which is removed periodically and refined to recover the gold and silver. The slimes are very rich, running 12,000 ounces in silver and 75 ounces to the ton in gold.

The cathodes, weighing about 130 pounds each, are melted in special furnaces, in which the copper is treated to remove gases and oxygen. The copper is then cast into various shapes for shipment. The approximate composition of this refined copper is shown by the following table:

TABLE 29.—APPROXIMATE COMPOSITION OF REFINED COPPER¹

Constituent	Percentage
Copper.....	99.92 to 99.97
Oxygen.....	0.01 to 0.02
Silver.....	0.001
Gold.....	0.00001
Sulfur.....	0.003
Iron.....	0.0001
Nickel.....	0.0015
Arsenic.....	0.0015
Antimony.....	0.0015

¹ Data from Anaconda Copper Mining Company.

It is of interest to note in connection with the trace of nickel occurring in the refined copper that, in the United States in 1927, no less than 1,719,518 pounds of nickel was saved from the slimes obtained from the electrolytic refining of copper.

MODE OF OCCURRENCE OF COPPER ORES

Copper ores are found in nearly all the existing types of ore deposits and in igneous, sedimentary, and metamorphic rocks. The following are their most important modes of occurrence:

1. Vein or fissure deposits (Butte, Montana; Globe and Morenci, Arizona).
2. Disseminated deposits.
 - a. Native copper in various rocks (Lake Superior region; Kennecott, Alaska; and Coro-Coro, Bolivia).
 - b. Sulfides in porphyry and schists (Bingham, Utah; Bisbee, Ray, Miami, Ajo, and Morenci-Metcalf, Arizona; Ely, Nevada; Santa Rita and Burro Mountain, New Mexico; Cananea, Sonora, Mexico; and Chile).
 - c. Sulfides and oxidized minerals in sedimentary rocks (Oklahoma, Texas, New Mexico, Arizona, and Germany).
3. Lenticular deposits in schists (Jerome, Arizona; Foothill and Shasta districts, California; Ducktown, Tennessee; and Prince William Sound, Alaska).
4. Replacement deposits in limestones near igneous rocks (Bisbee, Globe, and Silverbell, Arizona; Bingham, Utah; and Ely, Nevada).

This list includes the larger deposits of copper in the United States. There are hundreds of small ones the majority of which would fall into one of the above groups.

Vein or Fissure Deposits.—The mineral aggregate of the vein or fissure type of deposit either fills a fissure or replaces the country rock at the

side of it. The development of the fissures may have been accompanied by faulting. The copper sulfides are the chief ore minerals of these deposits, and quartz is the most common gangue mineral. The boundary between the ore and the wall rock may be sharp or indefinite. At Butte, Montana (the most noted region where this type of deposit is found), the solutions depositing the ore were hot and not only replaced the wall rock but also altered it beyond the vein.

Disseminated Deposits.—Disseminated deposits form some of the largest and most valuable copper reserves in the United States. Many authors do not classify the native copper deposits as disseminated deposits but make a separate group for them. They are, however, disseminated deposits, as the copper ore is disseminated through the country rock, and it is necessary to mine and treat all the rock in order to recover the metal. The tenor of disseminated deposits varies from a 0.5 per cent copper content for the native copper deposits of the Lake Superior region to a 2.5 per cent copper content for some of the porphyry coppers of the west.

Native Copper in Various Rocks.—Native copper ores consist of grains of native copper scattered through the rock. In the Lake Superior district (the most noted region where these ores occur), the copper is in volcanic rocks. It occurs in holes in lava flows; in small fissures in them; and as a cementing material in conglomerates and ash beds that lie between the lava flows. In the Coro-Coro deposits of Bolivia, native copper is disseminated through a sandstone.

Sulfides in Porphyry and Schists.—Disseminated deposits of copper sulfides include the great deposits found in various places in Utah, Arizona, Nevada, and other western states. The ore minerals are chiefly chalcocite and chalcopyrite, but near the surface the oxidized minerals occur. The majority of the deposits are in porphyries, but some are in other igneous rocks, and those of the Ray and Miami districts in Arizona are partly in schists. The minerals occur as grains in joints and fissures and scattered through the rock. The deposits are large and lie as tabular masses at varying distances below the surface. The overlying leached zone may be several hundred feet thick but usually is about 200 feet or less, and the sulfide zone may be 300 or 400 feet thick. Where the overlying rock is thin enough, it is removed and the ore is mined from an open cut.

Sulfides and Oxidized Minerals in Sedimentary Rocks.—Copper in the form of the sulfide and, to a minor extent, the oxide and native metal is found widely disseminated in sedimentary rocks. The "red beds" of Oklahoma, Texas, Colorado, New Mexico, and Arizona contain such deposits. They are of no economic importance. The copper shale deposit at Mansfeld, Germany, belongs to this class and constitutes Germany's chief source of the metal.

Lenticular Deposits in Schists.—Lenticular copper deposits in schists consist of the copper sulfides in lenses and pod-shaped or pipelike masses. They are often of large size. These tabular bodies have largely replaced the schist.

Replacement Deposits in Limestones near Igneous Rocks.—Many important copper deposits have been formed by solutions emanating from igneous rocks and depositing their mineral content as a replacement of parts of the country rock. Many of the deposits in the Arizona districts are of this type, as well as those in Utah and Nevada. As a rule, they are very irregular in shape and consist of pyrite, chalcopyrite, sphalerite, chalcocite, calcite, and quartz.

PRINCIPAL COPPER DISTRICTS OF THE UNITED STATES

There were no less than 30 districts in the United States whose production of copper was more than 1,000,000 pounds in 1927. Their

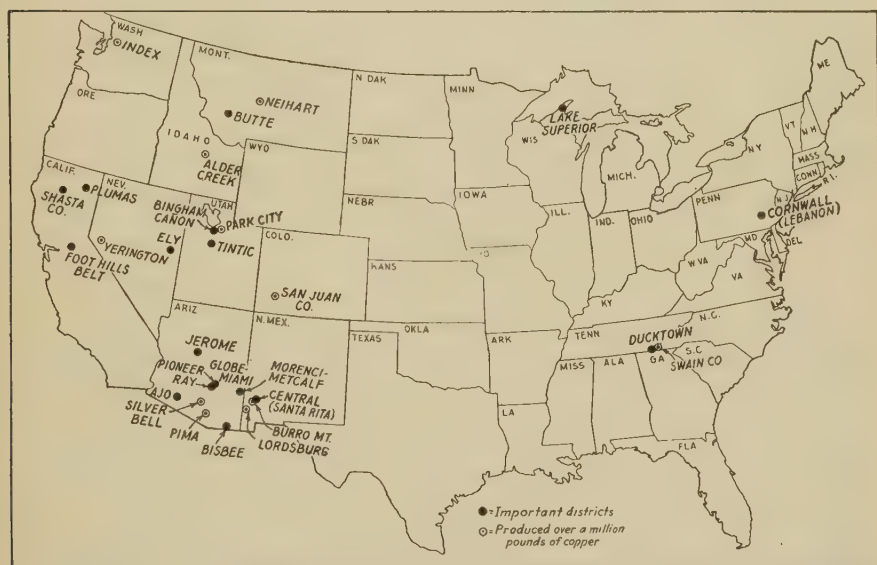


FIG. 56.—Copper deposits of the United States. Solid black round areas represent important districts; the others, those that have produced over a million pounds of copper.

location is shown on the map of copper deposits (Fig. 56). Seventeen of them have each produced at least 0.4 per cent of the total output of the United States to the end of 1927. These districts, the date of their initial production, the total amount of copper each has produced, and their percentages of the total for the United States are given in the following table:

TABLE 30.—COPPER PRODUCTION IN SOME OF THE PRINCIPAL DISTRICTS OF THE UNITED STATES TO THE END OF 1927¹

District or region	State	Date production began	Production, pounds	Percentage of U. S. total production	Rank
Butte.....	Montana	1868	9,391,729,000	23.94	1
Lake Superior.....	Michigan	1845	7,835,929,000	19.98	2
Bisbee.....	Arizona	1880	3,594,420,000	9.16	3
Bingham.....	Utah	1896	3,335,577,000	8.50	4
Globe-Miami.....	Arizona	1881	2,779,043,000	7.08	5
Jerome.....	Arizona	1883	Not published	.....	6
Morenci-Metcalf.....	Arizona	1873	1,781,228,000	4.54	7
Ely (Robinson).....	Nevada	1908	1,269,565,000	3.24	8
Central (and Santa Rita).....	New Mexico	1800	987,392,000	2.52	9
Ray (Mineral Creek).....	Arizona	1911	950,132,000	2.42	10
Shasta County.....	California	1897	624,324,000	1.59	11
Ajo.....	Arizona	Not known	521,857,000	1.33	12
Ducktown.....	Tennessee	1850	503,188,000	1.28	13
Plumas County.....	California	1865	199,079,000	0.51	14
Pioneer.....	Arizona	Not known	183,887,000	0.47	15
Tintic.....	Utah	1880	176,389,000	0.45	16
Foothill belt.....	California	1862	172,211,000	0.44	17

¹ U. S. Mineral Resources, 1927, Part 1, p. 688.

BUTTE, MONTANA

The Butte district is one of the greatest copper-producing areas in the world and the greatest in the United States. The mines are located in and about the city of Butte, Silver Bow County, in the southwestern part of Montana. Aside from its great copper production, the district is the largest in the United States in point of population. It produces 96 per cent of all the metals produced in Montana; 68 per cent of the production is copper, and the remainder is silver, zinc, gold, and lead.

History.—Butte first came into prominence as a gold camp in 1864, but the gold production reached its maximum in 1868 and declined rapidly. Silver was discovered during this early period, though little was mined. Several silver mines were opened in 1875 and 1876, and silver mining was active until in 1892, when, due to the low price of the metal, most of the mines were closed. The silver production today (1928) exceeds that of the earlier period, even though it is produced as a by-product in the refining of copper. Copper, like the gold and silver, was discovered during the sixties; but it was not until 1879, when the first smelter was started, that real production began. Previously, only very

rich ore (\$50 to \$200 per ton) had been mined, and it was sent to Baltimore, Maryland, for treatment.

The first railroad reached Butte in 1881, which marked, of course, the beginning of the real development of the district. Marcus Daly organized the Anaconda Silver Mining Company in 1881, but it was soon discovered that instead of a low-grade silver mine they had an enormously rich copper mine, for great solid bodies of chalcocite had been found. In 1883, the Anaconda smelter was built at Anaconda (25 miles west of Butte), and most of the ores are still treated there. Later, when electrolytic refining became so firmly established, the great refining plant at Great Falls, Montana, was built. By taking advantage of the falls in the Missouri River, large quantities of electrical power are produced cheaply at this plant.

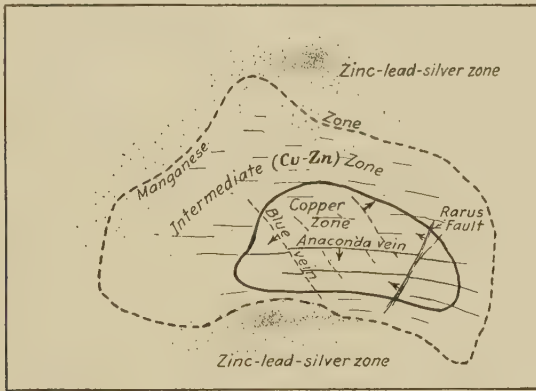


FIG. 57.—Ideal sketch of the metalliferous zones and the position of the major vein and fault systems at Butte, Montana. Position of boundary lines is arbitrary and approximate only, though based on best data available. Definite lines between zones do not exist. Scale, 1 mile = 1 inch. (Data from Sales; Weed; and U. S. Mineral Resources.)

More or less continual lawsuits (due to the so-called “apex law”) during the nineties finally brought the Amalgamated Copper Company into existence in 1899. Since then, the district has made rapid progress.

Geology of the Butte Area.—Several different igneous rocks occur in the Butte area, but the ore veins are confined to a dark-grained rock known as the “Butte granite” [really a quartz monzonite] (p. 30). Felsite (rhyolite) dikes cut the granite. These rocks are part of a great batholith known as the “Boulder batholith,” of late Cretaceous or early Tertiary age.

The intrusion of the granite was followed by several periods of fissuring and faulting (Fig. 57). The most important of these is an east-west system of fissures that dip steeply southward. These are known as the “Anaconda system,” and they occur throughout the district. The next most important series of fissures (accompanied by more or less

faulting) strikes northwest-southeast and dips dominantly to the southwest. This set of veins is known as the "Blue system." The displacement along the faults may amount to 300 feet but is normally much less. These two systems of veins are the source of most of the ore of the district, the Anaconda veins furnishing 60 per cent, and the Blue system 30 per cent.

The next movements which took place were dominantly movements of faulting. The faults cut and displace the two mineralized systems just described. The most prominent fault is the Rarus, which strikes northeast and southwest (Fig. 57). These faults have greatly increased the difficulty of mining in the district.

Mineralogy of the Butte Ores.—The Butte district produces *copper*, *zinc*, *silver*, *lead*, and *gold*. In addition to these major metals, *manganese*, *arsenic*, *tellurium*, and *cadmium* are produced.

Copper Ores.—The Butte district is noted for its production of *chalcocite* and *enargite*, but other copper minerals are important, also. The minerals of the copper ores and their sequence (oldest first) is as follows: quartz, pyrite, *sphalerite*, *enargite*, *tennantite* ($4\text{Cu}_2\text{S} \cdot \text{As}_2\text{S}_3$), *bornite*, *chalcopyrite*, *chalcocite*, *covellite*, and *rhodonite*. The importance of the various copper minerals at Butte has been estimated by Weed¹ as follows:

	Percentage of Butte's copper production
Chalcocite.....	75.00
Enargite.....	20.00
Bornite.....	4.00
Covellite.....	0.50
Chalcopyrite.....	0.50

Other estimates have been given which do not assign such a high percentage to chalcocite. The silver and gold occurring in the copper minerals at Butte accounted for 61 per cent of Montana's silver production and 45 per cent of her gold production in 1926.

Zinc Ores.—The zinc ores consist dominantly of *sphalerite*, but in the intermediate copper-zinc zone they also contain the minerals of the copper zone. The zinc ores of the zinc-lead-silver zone contain *sphalerite*, *silver-bearing galena*, and *pyrite*. *Rhodonite* and *rhodochrosite* are gangue minerals. The composition of the zinc ore produced in the largest zinc-producing mine in Montana, the Black Rock mine of the Butte and Superior Mining Company, is given in the following table:

¹ WEED, W. H., U. S. Geol. Survey *Prof. Paper* 74, p. 72, 1912.

TABLE 31.—THE METALLIC CONTENT OF THE 299,857 TONS OF ZINC ORE PRODUCED BY THE BUTTE AND SUPERIOR MINING COMPANY, BUTTE, MONTANA, 1926¹

Metal	Amount produced	Average metallic content per ton	Value
Zinc.....	69,790,230 lb.	11.6400 per cent	\$5,009,267.25
Lead.....	8,444,990 lb.	1.4100 per cent	675,599.20
Copper.....	1,486,822 lb.	0.2500 per cent	208,155.08
Silver.....	1,479,802 oz.	4.9300 oz.	923,596.45
Gold.....	1,348 oz.	0.0045 oz.	27,861.16

¹ U. S. *Mineral Resources*, 1926, Part 1, p. 412.

Silver Ores.—Silver ores, as such, are unimportant in the Butte district. The silver comes from all three metalliferous zones the chief ore minerals of which have already been noted.

Mode of Occurrence of the Ores.—Although some of the ores occur in veins of the filled-fissure type, their dominant mode of occurrence is as replacement veins. The ore consists of disseminated grains of sulfides scattered through the altered rock, though locally the minerals form solid masses of ore. The alteration and replacement may extend many feet from the fissure; or, if a series of fissures are closely spaced, the intervening rock is converted into an ore body. Some ore bodies mined are 30 feet wide.

The upper part of the copper veins is leached to a depth of 300 to 400 feet. Just at the top of the sulfide zone, enormously rich masses of massive secondary chalcocite occurred. This fact led to the belief that all the chalcocite found below this level (it extends to the bottom of the deepest mines, 3,800 feet) was also due to secondary enrichment. R. H. Sales, chief geologist of the Anaconda Copper Mining Company, has shown, however, that the chalcocite occurring below the massive chalcocite is primary.

The ores show a more or less zonal arrangement (Fig. 57). The copper ores are in the central part of the area and grade outward into a copper-zinc zone, which, in turn, grades into a zinc-silver-lead zone. The zinc ores are principally on the north, west, and south sides of the copper area. The principal silver ores lie north of the copper zone, but some silver occurs with all the zinc ores as well as with the copper ores. The latter, however, are relatively free from zinc.

Origin of the Ores.—The primary ores of the Butte area were deposited by hot magmatic solutions that came from the Boulder batholith. In addition to the metals, these solutions carried sulfur, arsenic, and mineralizing gases. The solutions altered the granite to sericite (a fine-grained muscovite) and quartz and deposited the metallic sulfides they carried in the zonal arrangement which they now occupy.

The massive chalcocite occurring at the top of the sulfide zone is due to secondary enrichment, the primary copper minerals of several hundred feet of ore veins above having been leached to produce it. A few minerals in small quantities are also of secondary origin; for example, silver in the oxidized zone.

Production of Butte District.—The enormous production of the Butte district must be noted. From 1868 to 1927, it has produced 9,391,729,000 pounds of copper. This is 23.94 per cent of the total copper production of the United States during that time. Although known as a copper district, one-fourth of the total mineral values of the Butte district is due to other metals. The total mineral production of this locality from 1882 to 1926 is given in the following table:

TABLE 32.—TOTAL YIELD OF ALL METALS OF BUTTE, MONTANA, DISTRICT, 1882–1926¹

Metal	Amount produced	Value
Copper.....	9,142,442,675 lb.	\$1,413,283,278
Silver.....	422,430,774 oz.	309,548,635
Zinc.....	2,133,803,734 lb.	180,208,892
Gold.....	1,699,557.2 oz.	35,132,987
Lead.....	242,532,647 lb.	16,684,771
Total value.....	.....	\$1,954,858,563

¹ U. S. Bur. Mines, 1926.

The Anaconda Copper Mining Company is the largest producer of copper and silver in the district. The company has large smelters at Anaconda and a large electrolytic plant at Great Falls. It is one of the largest metal-mining enterprises in the country and produces, in addition to copper and silver, zinc, lead, arsenic, and tellurium. The company, like many similar organizations, has its own coal mines and forests and, in order to market its metals to the best advantage, converts the copper and zinc into brass and numerous other alloys. This is done through the American Brass Company, which the Anaconda Company controls. It also manufactures sulfuric acid and fertilizers.

LAKE SUPERIOR COPPER DISTRICT, MICHIGAN

The second greatest copper district in the United States is the Lake Superior district, and it is the greatest native copper mining district of the world. It is located in the vicinity of Houghton, Michigan, on Keweenaw Peninsula. The ores are found in a belt striking north-east and southwest. This belt extends from northern Wisconsin, along Keweenaw Peninsula, appearing on Isle Royal in Lake Superior

and across the lake at Michipicoten, Ontario. The chief producing belt, however, is about 70 miles long and extends about 45 miles southwest and 25 miles northeast of Houghton.

Although at first, mining was on copper exposed at the surface, it has followed the ores underground to a vertical depth of over a mile. Some of the vertical shafts are among the deepest in the world, one of the Tamarack mine beings 5,800 feet deep. The inclined shafts are about a mile and a half in length.

History.—The history of the Lake Superior district has already been given in the general history of copper. From the date of its initial production in 1845, it led all copper districts in the United States until 1887. The development of the Montana mines caused its dethronement.

Geology of the Lake Superior Area.—The rocks of the Lake Superior district are basaltic lava flows and ash beds interbedded with some sedimentary rocks, mainly felsitic conglomerates and sandstones. The lavas were surface flows and, as a result, contain an abundance of amygdulæ, (cavities formed by the expansion of the gases in the lavas). These rocks have been cut by other igneous rocks, but the latter are unmineralized. The series has a total thickness of about 25,000 feet.

The lava flows, conglomerates, and sandstones are known as the "Keweenaw series" (pre-Cambrian in age), and the main ore lodes occur near the middle. The ore formations dip northwest about 40°, but the dip of the beds becomes less with depth and to the northwest near the lake shore. A fault which runs lengthwise of the Keweenaw Peninsula has dropped the pre-Cambrian beds downward, and horizontal Cambrian rocks form the surface of the southeast side of the peninsula.

Mineralogy.—The mineralogy of the Lake Superior copper ores is simple, the only copper mineral of importance being *native copper*. Native silver occurs with the copper. Minor quantities of sulfides are found, but they are not saved. There are no secondarily enriched minerals of any kind in the deposit. The important gangue minerals are calcite, quartz, zeolites, and epidote, and also several rare minerals. The quantity of gangue minerals is small compared with the amount of rock that must be mined and crushed to recover the copper.

Mode of Occurrence and Character of the Ores.—The *native copper* (and native silver) occurs as a filling in the amygdulæ of the lava flows and as a cement and replacement material in the conglomerates and ash beds. In the earlier days, veins of the ore were found. Some cross veins contain copper sulfides, but little attention is paid to them.

The most outstanding ore body of the district is the Calumet and Hecla conglomerate, in which the copper cements well-rounded pebbles of felsite-porphyry. The Calumet and Hecla mine, alone, has about 200 miles of underground workings in this conglomerate. The deep Tamarack shaft is on this ore bed. The conglomerate was about 10

feet thick at the surface but widened to 25 feet in the depths of the mine. The copper content of the surface ore was about 4 per cent, but that of the present ores is between 0.5 and 2 per cent.

The amygdaloidal ores furnish about two-thirds of the production of the district, but they are lower in grade than those of the conglomerate. The copper (and some silver) occurs in the amygdules of the basalts and, also, replaces the rock itself. The productive zones rarely exceed 40 feet in width and may be only 4 or 5 feet. The copper content of these ores averages from 0.5 to 1.5 per cent. The average of all the ores of the entire district in 1927 was 1.1 per cent copper.

Although of little importance at present, the veins should be mentioned because of the large masses of pure copper that have been obtained from them. One mass, recovered in 1880 from the Minnesota mine, weighed 500 tons and was 46 feet long, 18.6 feet wide, and 8.5 inches thick. Other large masses weighed as much as 100 tons.

Origin of the Ores.—Much has been written about the origin of the Lake Superior copper ores. Many geologists have favored the view that they were formed by descending waters that dissolved out the minute quantities of copper in the lavas and redeposited them in the lodes. A much more satisfactory explanation has recently been advanced by Butler and Burbank and seven collaborators.¹ These authors believe that the deposit was formed by magmatic solutions derived from the magma which gave rise to the Duluth gabbro below. The solutions were hot and under sufficient pressure to enable them to follow either the lode-forming layers or fissures upward from the magma. The solutions were similar to the average magmatic sulfide solution, and the native copper was deposited by their oxidation. The oxygen for this process was derived from the ferric oxide of the lavas.

Treatment of the Ore.—The treatment of the ore is very simple, as it is merely crushed in stamp mills, after which the copper is separated from the rock by water and finally melted in a furnace. In recent years, the companies have been reducing their losses of fine copper during separation by using the flotation method. The tailings produced under the old method have also been leached to recover the lost copper.

Copper Production of the Lake Superior District.—Although the Lake Superior district is the oldest copper camp in the United States, it is still responsible for over 10 per cent of the annual copper production of the country. From the date of its first output, 1845, until 1927, it produced 7,835,929,000 pounds. This was 19.98 per cent of the total copper production of the United States for that period. The reserves of the copper ore in the district are large.

¹ BUTLER, BURBANK, and others, *The Copper Deposits of Michigan*, U. S. Geol. Survey *Prof. Paper* 144, 1929.

BISBEE, ARIZONA

The Bisbee district is located in the Mule Mountains, Cochise County, southeastern Arizona, not far from the international boundary line between the United States and Mexico. The Bisbee district (known, also, as the "Warren district," from one of the discoverers) was discovered in the late seventies, but production did not begin until 1880. The story of the early days of the camp is the typical romance of mining. The development of the district was slow at first; but, once the geology and the character of the ores were understood, progress was assured, and Bisbee now ranks as the third copper district in the United States.

Geology of the Bisbee Area.—The geology of the district is simple. A series of Paleozoic sediments, mainly limestones and quartzites, was intruded during early Mesozoic times by a mass of granite porphyry. These formations, after much erosion which was accompanied by enrichment of ores, were buried under Cretaceous sediments. Subsequent folding and deep erosion have exposed the ores. The main ore bodies lie in a synclinal trough in Carboniferous limestone near the granite porphyry stock (see Fig. 58).

Mineralogy of the Ores.—In addition to copper, Bisbee produces silver, gold, lead, zinc, and manganese. The ore minerals can be divided into two groups, the *oxidized ores* and the *sulfides*.

The Oxidized Ores.—For 25 years after the Bisbee camp began to produce, the main yield came from the oxidized ores, which extended to 1,400 feet or more below the surface. The richness of some of the oxidized ores was remarkable, especially those of the Copper Queen (a name that was well deserved) mine. Some of them ran as high as 25 per cent copper. The chief oxidized minerals were *malachite*, *azurite*, *cuprite*, and *native copper*. Recently, an oxidized lead-silver ore has been produced from three or four of the mines. The iron oxides, calcite, and clay are the common gangue minerals of these ores.

The Sulfide Ores.—About 1904, important sulfide ore bodies were found. These consisted of *pyrite*, *chalcopyrite*, *bornite*, and, in certain mines, *galena* and small amounts of *sphalerite* and *magnetite*. Secondary sulfide enrichment has produced considerable *chalcocite*.

Mode of Occurrence of the Bisbee Ores.—The ores occur as replacements in the limestone, always near the porphyry stock. Near the contact with the porphyry, the limestone has been altered into a mass of contact-metamorphic minerals. The ore bodies have various forms, but the majority are lenticular and roughly follow the bedding of the limestones. Other ore bodies follow fissures, so are very irregular. The ore bodies dip, in general, to the southeast. In the northern part of the district, the secondary sulfides are above the present water level, and in the southern part both the oxidized and the sulfide ores are below it.



FIG. 58.—Bisbee, Arizona, 1904. The dark hill (Sacramento Hill) is an intrusive mass of porphyry. Churn drills were used to prove that it was a disseminated ore body. The mines are located in the limestone to the right but adjacent to the porphyry. (*Eng. Min. Jour.*, vol. CXXVI, p. 657, 1928.)



FIG. 59. Sacramento Hill in 1928 showing the large open cut from which 20,000,000 tons of waste rock (overburden) and 10,000,000 tons of ore (averaging about 1.7 per cent copper) have been removed. (*Eng. Min. Jour.*, vol. CXXVI, p. 657, 1928.)

Developments during the last 15 years have shown that excellent disseminated ores due to oxidation and sulfide enrichment occur in the porphyry. The only large outcrop of the granite porphyry (known as "Sacramento Hill") is largely ore and is being mined by open-cut methods (see Fig. 59).

Origin of the Ores.—The relationship of the porphyry to the contact-metamorphic and replacement deposits and the occurrence of disseminated deposits in the porphyry itself prove that the ores were formed by hot solutions derived from deeper portions of the porphyry. The ores have been enriched by both oxidation and sulfide enrichment. The position of the ore bodies with regard to the water level (already noted) shows that a part, at least, of the oxidation, leaching, and sulfide enrichment preceded the burial by the Cretaceous sediments and the subsequent folding.

Treatment of the Ores and Production of the Bisbee District.—During the early days of production, the ores, which were mainly the oxidized ores, were treated at a smelter in the Bisbee district, but the present sulfide ores are smelted at Douglas, Arizona, about 20 miles away.

The total production of the Bisbee camp to the end of 1927 was 3,594,420,000 pounds of copper. This is 9.16 per cent of the total copper production of the United States.

BINGHAM CAÑON, UTAH

The Bingham Cañon copper district is located in the Oquirrh Mountains in the southeastern corner of Salt Lake County, Utah, about 27 miles from Salt Lake City. The mines are near the upper part of the cañon (Fig. 60). The district was opened in 1865 as a gold-silver-lead camp; and, although some copper was then recognized in the ore, it was not until 31 years later (in 1896) that the importance of the copper deposits was recognized. It now ranks fourth in the total production of copper in the United States. In recent years, zinc has been added to the list of metals produced.

Geology of the Bingham Cañon Area.—The geologic section in the Bingham Cañon district is thick, but only the Upper Carboniferous beds contain the ores which are mined at present. These beds are from 12,000 to 15,000 feet thick. The thickest member is the Bingham quartzite, which includes several beds of limestone (some 300 feet thick). The general structure of the area is synclinal. A quartz monzonite porphyry has been injected into the beds, altering them considerably, especially the limestone members. The porphyry, which forms a stock, is strongly fractured and fissured.

Mineralogy of the Ores.—The primary copper minerals are *copper-bearing pyrite*, *chalcopyrite*, and *bornite*. These minerals were deposited

as replacement ores in the fissures of the porphyry and quartzite; and, after they had been exposed by erosion, the secondary oxidized minerals (not important as a source of copper) and the secondary sulfides *chalcocite* and *covellite* were formed. The minute black or blue grains of these two minerals are scattered all through the rocks.

In the limestones, excellent copper ores occur as veins and as replacements. They contain *pyrite*, *chalcopyrite*, and rarely *chalcocite* and *bornite*. Contact-metamorphic minerals, such as *garnet* and *specularite*, occur with some of the ores. *Gold* and *silver* are found in these ores.



FIG. 60.—View of Bingham Cañon, Utah, and the open-cut mine of the Utah Copper Company. (Photograph furnished by the Utah Copper Company.)

The lead-silver-zinc deposits contain *argentiferous galena*, *pyrite*, *sphalerite*, and some *chalcopyrite*.

Mode of Occurrence of the Ores.—The various ores of the district occur as *veins in the igneous rock* (porphyry) and the *sediments*; *replacements in the limestone*; *contact-metamorphic deposits*; and *disseminated deposits in the porphyry and adjacent quartzite*. The replacement deposits are the chief source of lead, silver, and zinc; the veins produce copper, gold, silver, and some lead. The chief source of the copper, however, is the disseminated deposits, which are about 415 feet thick. The leached zone above (overburden) averages 115 feet in thickness (see Fig. 61).

Origin of the Ores.—The deposits of the Bingham Cañon district were formed by hot solutions originating within the magma that gave rise to the quartz monzonite porphyry. The first period of mineralization occurred shortly after the intrusion of the porphyry and formed the contact-metamorphic and replacement deposits in the limestones. The alteration extended back for nearly 2,000 feet from the igneous rock. The second period of primary deposition took place largely in the fissured porphyry and quartzite. It was during this period that the primary disseminated deposits were formed. Following exposure by erosion, the copper was leached out of the upper part of these deposits and was carried downward to form secondary sulfide ores.

Methods of Mining and Production of the District.—The development of the copper deposits of the Bingham Cañon district has been due largely

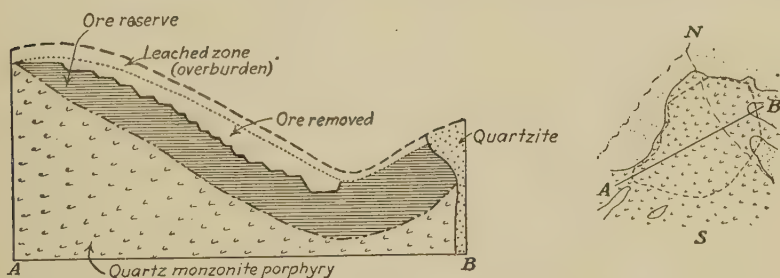


FIG. 61.—Cross section (along AB of small figure) of the ore body of the Utah Copper Company at Bingham Cañon, Utah. Small figure shows the porphyry and quartzite and, by dotted line, the area of copper ore. (Modified from Butler, U. S. Geol. Survey Prof. Paper 111, p. 358.)

to the Utah Copper Company. This company has one of the largest open-cut copper mines in the world (Fig. 60.) As Figs. 60 and 61 show, the ore is mined from a series of benches that extend up the face of the ore body. After the ore has been blasted down, electrically driven shovels of large capacity load it directly into the ore cars for shipment to the mills, some miles away. Near the end of 1928, nearly 50,000 tons were being sent through the concentrating mills every 24 hours. The amount of overburden removed daily exceeds the tonnage of ores. The maximum daily tonnage of both ores and overburden is 107,357 tons, which, according to the company's estimate, would require 2,147 fifty-ton cars for hauling. If each car were 40 feet in length, this would mean a train 16 miles long.

In 1926, the Utah Copper Company had an estimated reserve of 564,000,000 tons of ore that averaged about 1.1 per cent copper. Figures for the total amount of all the metals produced in the Bingham Cañon district from 1865 to 1928 are given in the following table:

TABLE 33.—THE PRODUCTION, BY METALS, OF THE BINGHAM CAÑON DISTRICT, 1865-1928¹

Metal	Production
Gold.....	2,538,930 oz.
Silver.....	75,185,060 oz.
Copper.....	3,679,548,945 lb.
Lead.....	1,859,766,752 lb.
Zinc.....	242,709,844 lb.

¹ Data from U. S. Bur. Mines.

The total value of this production of ores of the Bingham Cañon district has been estimated at \$843,530,202.

GLOBE-MIAMI DISTRICT, ARIZONA

The Globe-Miami copper district is located in Gila County, Arizona. Globe is the old mining center and is famous for the great productivity of the Old Dominion mine. It began producing copper in 1881 and now ranks fifth in the total production of that metal in the United States. The Miami deposits are 6 miles west of Globe and, although comparatively young (about 20 years old), are more important than those at Globe.

Geology of the District.—The rocks of the Globe-Miami district are of ages from pre-Cambrian to Mesozoic. The oldest is the Pinal schist, a formation found in other Arizona districts. Paleozoic sediments were deposited on this schist. Intrusions, represented by diabase and granite, occurred in Mesozoic times, and volcanic rocks are present as the result of extrusions in Tertiary times. Faulting occurred before and after the ores were deposited. The event of the greatest economic importance was the intrusion represented by the present Schultze granite, as the ores were derived from that intrusive mass.

Mineralogy of the Ores.—The ores are simple in composition. The primary minerals in both the lodes and the disseminated deposits were *pyrite* and *chalcopyrite*; rarely some *bornite*; and a little *specularite*, *sphalerite*, and *galena*. The ores carry some gold and silver. The lode at the Old Dominion mine contained oxidized ore minerals in the upper part of the mine (above 1,200 feet) and *chalcocite* in the sulfide zone. The disseminated sulfide ore in the schist is mainly *chalcocite*.

Mode of Occurrence of the Ores.—The most important ores occur as *disseminated deposits* in the Pinal schist and as *lodes* in shattered zones in the igneous rocks and sediments. The Old Dominion mine was a rich lode deposit. Where the lodes are adjacent to limestone, important replacement deposits occur. The disseminated ores in the Pinal schist are adjacent to the Schultze granite. This disseminated ore body ranges in thickness from a thin belt up to 300 feet and is about 2 miles long and $\frac{1}{4}$ mile wide. It lies between 200 and 400 feet below the surface at the east end of the belt and 1,000 feet below toward the west end.

Origin of the Ores.—The mineralization in the Globe-Miami district was by hot solutions evidently coming from the magma that formed the Schultze granite. The solutions deposited their mineral matter in the shattered ground (forming the lode), in the rocks adjacent to it (forming replacement deposits), and in the much-fissured Pinal schist.

Subsequent exposure to weathering agents resulted in oxidized deposits and in sulfide enrichment. A large part of the enrichment occurred in early Tertiary times.

Production of the Globe-Miami District.—The ore of the Old Dominion mine in this district formerly averaged over 5 per cent copper, but the supply of ore of that grade is now (1928) low. The major production at present is made from concentrating ore that averages 3.7 per cent copper. Two companies, the Miami Copper Company and the Inspiration Copper Company, have developed a great tonnage of disseminated ores. The former had an estimated reserve, in 1926, of 84,584,000 tons of ore that averaged 0.93 per cent and 7,000,000 tons that averaged 1.83 per cent copper. In 1926, this company produced over 3,793,000 tons of ore averaging 0.97 per cent copper. This production was made at a cost of 10 cents per pound. The Inspiration Company has a reserve of 90,000,000 tons of ore averaging about 1 per cent copper. In 1926, this company mined over 5,490,000 tons of ore that averaged 1.02 per cent copper. The company has about 129 miles of underground workings, which gives some idea of the magnitude of the mines.

The Globe-Miami district has produced a total of 2,779,043,000 pounds of copper since 1881, which is 7.08 per cent of the total copper production of the United States.

JEROME, ARIZONA

Jerome is located near the center of Arizona, in the northeastern part of Yavapai County. The earliest mining in the district began in 1876, but it was silver that was mined, not copper. As the mine (called the "United Verde") became deeper, some copper was found and a fair production of it was made until 1887 when the mine was practically abandoned. W. A. Clark of Montana bought the property in 1889, reopened it, and about 1894 discovered the rich pyritic copper ore. This discovery stimulated other prospecting, but the results were negative until 1914, when another enormously rich ore body was found on the United Verde Extension property. This property had been acquired in 1912 by James S. Douglas (son of Dr. James Douglas of Bisbee fame) after it had been condemned. Jerome now ranks as the sixth copper district in the United States.

Geology of the Area.—The rocks associated with the ores in the Jerome district are all pre-Cambrian in age. They consist of very fine-

grained schists, that were originally rhyolites, tuffs, and sediments. The Bradshaw granite is intrusive in these schists.

Mineralogy of the Ores.—The chief ore minerals of the Jerome district are *copper-bearing pyrite*, *chalcopyrite*, *sphalerite*, and *tennantite*; pyrite and chalcopyrite greatly predominate, however. The *copper carbonates* and *cuprite* were found above the 400-foot level, and a zone of good *chalcocite* just below it. The gangue minerals are quartz, sericite, and other minerals formed during the replacement. Lindgren states that the pyritic copper ores (of the United Verde mine) form one of the largest of such deposits in the United States and one of the largest known anywhere. No ore containing less than 2.5 per cent copper is mined in the district, and the average content is much higher, as is shown by the following table:

TABLE 34.—COMPOSITION OF THE ORE ON FOUR SELECTED LEVELS IN THE UNITED VERDE MINE, JEROME, ARIZONA¹

Stoping area, square feet	Percentage of copper of average-grade ore	Amount of ore per foot of depth, tons	Amount of copper per foot of depth, tons
37,520	5.60	4,461	249.8
36,090	5.18	3,902	202.1
48,860	7.99	6,138	490.4
88,650	8.57	10,811	926.5
Averages of above			
49,345	7.06	5,881	415.2

¹ LINDGREN, U. S. Geol. Survey Bull. 782, p. 70, 1926.

Mode of Occurrence of the Ores.—The copper ores of Jerome occur as pipelike replacement deposits in the rhyolitic schist. The ore body is about 700 by 800 feet in horizontal section and lies parallel to the structure of the schists. It dips steeply to the northeast. The ore has been mined to depths of 3,500 feet. Very similar types of ore occur in the two mines.

Origin of the Ores.—The deposits are due to the sulfides' having replaced parts of the schists. They were formed by solutions that evidently were rising. These solutions were probably derived from the intrusive magma that gave rise to the Bradshaw granite.

Production of the Jerome District.—The production of the district is unknown, because the United Verde Copper Company will not permit the publication of its production figures.

MORENCI-METCALF DISTRICT, ARIZONA

The Morenci-Metcalf copper deposits are in Greenlee County, Arizona. The Metcalf deposits are several miles north of the Morenci

deposits. The copper was discovered in 1872, and production began in 1873; but, as the ores were of low grade and far from a railroad, development was slow for many years. The district now ranks seventh in total production of copper in the United States.

The district is well known because of the classical report by Waldemar Lindgren on its contact metamorphism. His careful, detailed analysis of the process of contact metamorphism, as developed in this district, was a milestone in the study of mineral deposits. It was published in 1905.

Geology of the Area.—The rocks of the Morenci-Metcalf area are pre-Cambrian granites and schists; a series of Paleozoic limestones, sandstones, and shales; Cretaceous shales and sandstones; and Tertiary lavas (basalt, rhyolite, and andesite). Stocks and dikes of granite porphyry and quartz monzonite porphyry cut through all these earlier formations. The intrusion occurred in late- or post-Cretaceous times and affected intense contact metamorphism of the upper members of the Paleozoic series, especially the limestones and shaly limestones. The alterations extended hundreds of feet from the intrusive rock.

Mineralogy of the Ores.—The primary ore minerals of the district were *pyrite*, *chalcopyrite*, and *sphalerite*. Minor quantities of other minerals occur with the ores. *Copper carbonates and oxide* and other oxidized minerals were the principal minerals mined in the early days of the district. The leaching of the copper and its downward movement below the water level (especially in the original disseminated deposits) produced the *chalcocite* ores so extensively mined at present. The contact metamorphism gave rise to garnet, epidote, diopside, magnetite, tremolite, and quartz.

Mode of Occurrence of the Ores.—The copper ores are in *contact-metamorphic deposits* (which contain zinc, also); *fissure-vein deposits* (also with zinc); *replacement deposits in limestones*; and *disseminated deposits*. The original primary ores in all these types of deposits were of low grade, but all have undergone secondary enrichment, those of the contact-metamorphic deposits the least of all. The disseminated ores are the most important ones at the present time.

Origin of the Ores.—There is no doubt but that the ores of the district are directly related to the igneous intrusion. The alteration produced by the solutions is of varying degree. It began with the very hot solutions at the contact and continued until the deposition of the disseminated sulfides occurred in the fissured porphyries and other rocks. Oxidation and enrichment of the ores followed the exposure of the area at the surface.

Production of the District.—From 1873 to 1927, the Morenci-Metcalf district produced 1,781,228,000 pounds of copper, which was 4.54 per cent of the total copper production of the United States at that time.

The district possesses large reserves of chalcocite ore. The ore body of the Phelps Dodge Corporation averages 2 per cent copper.

ELY, NEVADA

The Ely district is located in the central part of White Pine County, Nevada. The copper deposits lie a few miles west of Ely. The district ranks eighth in the production of copper in the United States, in spite of the fact that it began to produce as late as 1908.

Geology of the Area.—The Upper Paleozoic sediments, which are largely limestones, were intruded by an igneous mass, now represented by a stock and numerous dikes of monzonite porphyry. The sedimentary rocks have been folded and extensively faulted. Mild contact metamorphism resulted from the intrusion, accompanied by the deposition of sulfides of copper, lead, and zinc. Unless subsequently enriched, these ores are of little value, however. Fissuring of the porphyry followed its solidification. The fissures furnished a place for deposition of the ores.

Mineralogy.—The primary ore minerals of the area were *pyrite* and *chalcopyrite*, accompanied by quartz as the chief gangue mineral. In the contact phases, some *sphalerite* and *galena* are present. The ores mined at present (1928) are the secondary sulfides, which consist dominantly of *chalcocite* on the pyrite and chalcopyrite.

Mode of Occurrence of the Ores.—The chief ores of value in the Ely district are the disseminated deposits of copper sulfides, which are found almost entirely in the porphyry. These sulfides occur in fissures in the porphyry and replacing it. A leached zone containing scattered oxidized minerals is from 50 to 200 feet thick (averages 100 feet). The sulfide zone averages about 220 feet in thickness.

Origin of the Ores.—The copper sulfide ores of the Ely district were deposited by hot solutions that penetrated the fissured monzonite porphyry. These solutions came from the lower parts of the igneous mass. Subsequent secondary changes converted the original disseminated deposit into a workable ore body.

Production of the Ely District and Methods of Mining.—The total copper production of the Ely district to the end of 1927 was 1,269,565,000 pounds, which was 3.24 per cent of the total copper production of the United States. The ores of this area, unlike those of so many copper mines, carry higher values in gold than they do of silver. The total production of all the metals that have been produced here is given in the following table:

TABLE 35.—TOTAL PRODUCTION OF ALL METALS IN THE ELY DISTRICT, NEVADA, 1904-1927¹

Metal	Production
Gold.....	486,663 oz.
Silver.....	1,762,885 oz.
Copper.....	1,269,565,000 lb.
Lead.....	4,474,441 lb.
Zinc.....	6,070,025 lb.

¹ Data from U. S. Bur. Mines.

The total value of the production represented in this table is \$229,608,336.

For 20 years, the Nevada Consolidated mine has been operated from an open cut by steam shovels; but, as the ores extend nearly 600 feet below the surface, the company has sunk a large shaft, 711 feet deep, and will mine by underground methods in the future. The company has a large reserve of ore that averages from 1.5 to 2 per cent copper. The porphyry below the ore contains less than 0.4 per cent copper.

CENTRAL DISTRICT (SANTA RITA) NEW MEXICO

The Santa Rita district is located in Grant County, New Mexico, about 15 miles east of Silver City. Santa Rita was one of the earliest

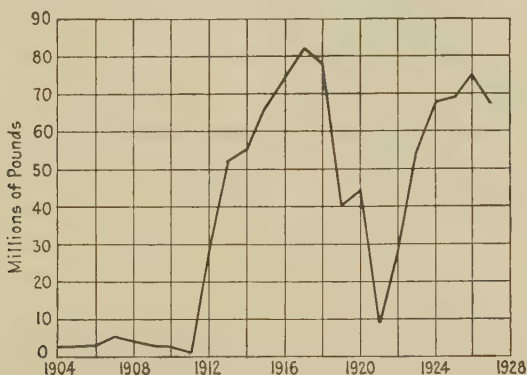


FIG. 62.—Production of copper, from 1904 to 1927, in Central District (Santa Rita), New Mexico. (Data from U. S. Bur. Mines.)

copper districts worked in the United States, at least it is reported that the Spaniards mined native copper there about 1800 and took it to Mexico City to be coined into money. The district produced from time to time in a small way, but the real production began in 1912 (Fig. 62) when a large low-grade deposit was opened and worked by steam shovels. The district now ranks ninth in total production in the United States.

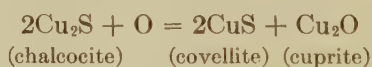
Geology of the District.—The lower rocks of the area are Paleozoic limestones and quartzites, which are separated by an unconformity from the Cretaceous rocks above. Tertiary lavas and tuffs are above the latter. Several groups of igneous rocks occur, but a granite porphyry

which cuts the earlier intrusives and sediments carries the ore. At the contact of this porphyry (really a quartz monzonite porphyry), a contact-metamorphic zone developed in the sediments. Folding and faulting have occurred, but they had no influence on the ores. During late Cretaceous and early Tertiary times, the region was peneplained, which favored the downward movement of leached materials.

Mineralogy of the Ores.—The primary ore minerals of the area were *pyrite* and some *chalcopyrite*. The ores mined at present contain chiefly *chalcocite*, *cuprite*, and *native copper*. Numerous other secondary minerals occur which are not important as ore minerals. The first minerals mined in the district were chiefly *cuprite* and *native copper*.

Mode of Occurrence of the Ores.—The sulfide ore bodies are disseminated deposits occurring in the porphyry, which has been extensively altered by hot solutions to *sericite* and secondary *quartz*. The *native copper* and *cuprite*, occurring also as disseminated deposits, are confined to the *quartzites* adjacent to the porphyry. Contact-metamorphic deposits occur, but they are unimportant as a source of copper.

Origin of the Ores.—The mineralizing solutions were hot magmatic waters coming from the magma which produced the quartz monzonite porphyry. They altered the porphyry and deposited the *pyrite* and copper sulfides in it. During the peneplanation that followed the primary mineralization, the copper in the upper parts of the porphyry was carried downward and deposited as *chalcocite* by replacement of the *pyrite*. The lowering of the ground-water level permitted the oxidation of the *chalcocite* to *cuprite* and *native copper*. The possible reaction for the formation of *cuprite* is as follows:



Covellite is the comparatively unstable copper sulfide, so the amounts of it formed in this reaction probably changed back into *chalcocite*, as none of it is found with the ores.

Production of the District and Mining Methods.—The Santa Rita district, from 1800 to 1927, produced 987,392,000 pounds of copper, which was 2.52 per cent of the copper production of the United States. Essentially all of the production is made by one organization, the Chino Copper Company, now owned by the Nevada Consolidated Copper Company. The open-cut mining method is still used, but the company is also sinking shafts to reach a large underground ore body.

RAY, ARIZONA

The Ray district (formerly, the Mineral Creek district) is located about 6 or 8 miles north of Kelvin in Pinal County, Arizona. It is

about 20 miles southwest of Globe. The district is a recent development, as production began in 1911. The large yearly tonnages produced, however, quickly made it an important area, and it now ranks as the tenth copper district in the United States.

Geology of the District.—The geology of the Ray district is simple. A granite porphyry, which apparently is related to the Schultze granite of the Globe-Miami district to the northeast, is intrusive in the pre-Cambrian Pinal schist.

Mineralogy.—The primary minerals were *pyrite* and *chalcopyrite*. Some oxidized copper minerals occur, but the ore mined is secondary *chalcocite* that has replaced the primary sulfides.

Mode of Occurrence of the Ores.—The ores of the Ray district are disseminated deposits which occur dominantly in the schist but also in parts of the porphyry. The ore body is an elongated oval belt 1.5 miles

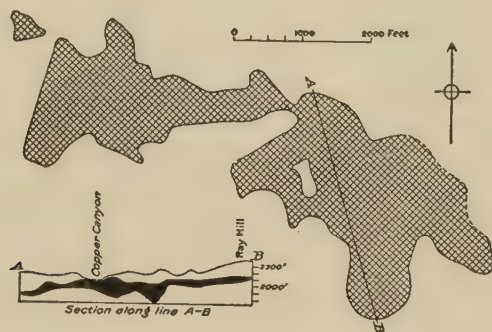


FIG. 63.—Plan and section of the ore bodies as developed by underground exploration in the Ray district, Arizona. (Ransome, U. S. Geol. Survey Prof. Paper 115, p. 146, 1919.)

long, 0.5 miles wide, and, though attaining a thickness of 400 feet in some places, having an average thickness of 100 feet (Fig. 63). It lies from 10 to 300 feet, though usually about 250 feet, below the surface.

Origin of the Ores.—The solutions that deposited the ores came from the magma that gave rise to the granite porphyry. The fissures in the Pinal schist and in the porphyry furnished the places for the deposition. The secondary enrichment which produced the chalcocite was independent of the present water level, having developed long before the present topography was formed.

Production of the District.—The Ray district produced, from 1911 to 1927, 950,132,000 pounds of copper, which was 2.42 per cent of the total copper production of the United States. The chief production of the district is made by the Ray mine of the Nevada Consolidated Copper Company. It was estimated at the end of 1926 that the company had a reserve of over 70,000,000 tons of ore averaging 2.07 per cent copper.

SHASTA COUNTY, CALIFORNIA

The Shasta County district lies in northern California, near the head of the Sacramento River and a few miles north of Redding. It began to produce in 1897 and is now the eleventh in copper production in the United States.

Geology of the District.—The geology of the district is complex. The original sediments, which are now largely slates and other metamorphic rocks, contain many intrusive igneous rocks only one of which, however, is of economic significance. It is an alaskite porphyry (similar to a granite porphyry), and the ore bodies are all related to it.

Mineralogy of the Ores.—The ores are great masses of *pyrite* and *chalcopyrite*. They carry considerable *gold* and *silver*. The gangue minerals include quartz, barite, calcite, and gypsum.

Mode of Occurrence of the Ores.—The ores of the district occur as replacement deposits in intensely crushed and shattered zones of the porphyry and in a few places extend into the surrounding slates. The ore bodies form great tabular masses some of which are 1,200 feet long, 300 feet wide, and 50 to 300 feet thick. One of these, the Iron Mountain, contained originally probably 20,000,000 tons. The ore bodies lie fairly flat so are in a favorable position for mining.

Origin of the Ores.—The deposits of the area were formed by magmatic waters' replacing the original porphyry and slates along the shattered zones, probably at depths of 5,000 or 6,000 feet. The solutions altered the porphyry along the lodes to sericite and other secondary minerals.

Production of the District.—The Shasta County district has produced to the end of 1927 a total of 624,324,000 pounds of copper, which is 1.59 per cent of the total production of the United States. Although for many years its production was very large, it has recently fallen off and may continue to do so.

AJO, ARIZONA

The Ajo district is in the Ajo Mountains in western Pima County, Arizona. This area represents another of the recent developments of low-grade copper deposits. The New Cornelia Copper Company's mine includes the entire ore body, which covers about 55 acres. The district is twelfth in the total production of copper in the United States.

Geology of the Area.—The original rocks of the area were rhyolite (felsite) lava flows and interbedded rhyolite tuffs. A monzonite porphyry is intrusive in the rhyolites, by which they are bowed up.

Mineralogy of the Ores.—Few districts have a simpler group of minerals than the Ajo. The primary ore minerals are *chalcopyrite* and *bornite*, and the secondary ones are *malachite* and *chrysocolla*. Malachite comprises 85 per cent of the production from the secondary ores.

Mode of Occurrence of the Ores.—The copper ores occur as well-defined veins (formerly worked) in the porphyry and rhyolites and as disseminated deposits in the same rocks. Both the oxidized and sulfide ores occur as disseminated deposits. The former extend from the surface to a common plane about 20 feet below the deepest valleys, and the latter lie below this plane. The sulfide ores attain a maximum thickness of 600 feet.

Origin of the Ores.—The primary copper ores were due to the waters coming from the magma that gave rise to the porphyry. Deposition of the sulfides occurred in the fissured part of the intrusive itself. Subsequent oxidation of the top of the deposit formed the carbonate ore body.

Production of the Ajo District.—The Ajo district is noted for its production of copper carbonate ore. This ore originally amounted to 12,000,000 tons, but in 1925 only about 3,000,000 tons remained. The ore was averaging 1.2 per cent copper in 1926. The copper is recovered by leaching. The sulfide ores run about 1.6 per cent copper. From 1907 to 1927, the Ajo district produced 521,857,000 pounds of copper, which was 1.33 per cent of the total copper production of the United States.

DUCKTOWN, TENNESSEE

The Ducktown district is located in Polk County in the extreme southeastern corner of Tennessee. The earliest date of production was 1850, and Ducktown is now the thirteenth copper district in the United States.

Geology of the Area.—The country rocks are mainly schists of various kinds that have resulted from the metamorphism of Cambrian sedimentary rocks. These are cut by dikes of several kinds of igneous rocks the youngest of which is a gabbro. The schist series strikes northeast and dips southeast. Locally, the schists are sharply folded (Fig. 64) and considerably faulted. A part of the metamorphism preceded mineralization.

Mineralogy of the Ores.—The primary ore minerals consist of *pyrrhotite*, *pyrite*, *chalcopyrite*, and some *bornite* and *sphalerite*. The secondary minerals are *chalcocite*, residual *iron ores*, and some *oxidized copper minerals*.

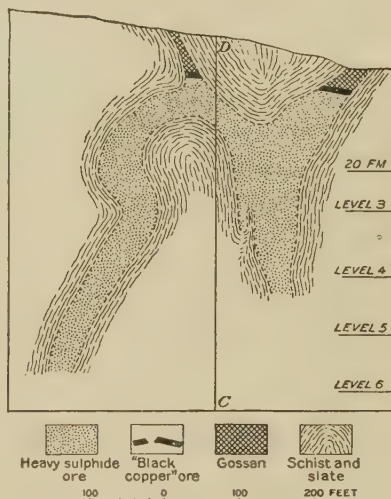


FIG. 64.—Sketch showing the gossan (leached zone), chalcocite zone (black area), and primary sulfide ore below. Ore body in Mary mine, Ducktown, Tenn. (After Emmons and Laney, U. S. Geol. Survey Prof. Paper 139, p. 68.)

Mode of Occurrence of the Ores.—The residual deposit of iron ore (gossan) developed over the sulfide ores. In places, it is 100 feet thick. The oxidized copper minerals occur in this zone. At the base of the leached zone, the rich, but thin (3 to 4 feet thick), zone of secondary chalcocite occurs, and below this are the replacement deposits of the primary sulfides that have not been enriched (see Fig. 64). These primary sulfides now constitute the chief ore of the district.

Origin of the Ores.—The primary sulfides were deposited by magmatic waters from an igneous mass below. They were apparently the result of the replacement of a limestone member of the original sedimentary series. The period of mineralization was evidently later than the major period of metamorphism, as the ores are less metamorphosed than the associated rocks. Leaching and secondary sulfide enrichment developed the rich chalcocite zone.

Copper Production and Associated Industries of the Ducktown District.—From 1850 to 1927, the Ducktown district produced a total

of 503,188,000 pounds of copper, which was 1.28 per cent of the total copper production of the United States. Some iron is also produced from the residual deposits. Large quantities (1,000 tons daily) of sulfuric acid are made from the sulfur fumes from the smelter. The sulfuric acid plant is one of the largest in the world. Part of the acid produced is used to convert a phosphate rock, mined in central Tennessee, into a high-grade fertilizer.

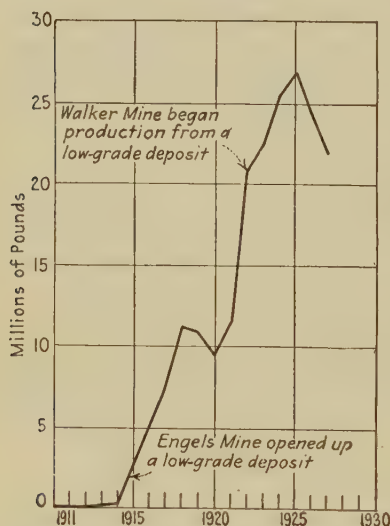


FIG. 65.—Production of copper in Plumas County, California, 1911 to 1928. Shows the effect of working a low-grade deposit by large-scale methods.

PLUMAS COUNTY, CALIFORNIA

The Plumas County district is about 20 miles long and lies wholly in Plumas County in the north-central part of California, well up on the side of the Sierra Nevada Mountains. Mining began in this district in 1865, but it has been only since 1915, when the Engels

Copper mine began its large-scale operations, that the production has been important (Fig. 65). The Walker mine of the Anaconda Copper Mining Company, about 20 miles from the Engels mine, began production in 1922. The output of the district was doubled that year. Many small mines have been opened in the area between the Engels and Walker mines. The area ranks fourteenth in total production of copper in the United States.

Geology of the District.—The country rock at the Engels mine is a granodiorite which is believed to be a part of the great batholithic mass of the Sierra Nevadas. That at the Walker mine is thought to be of the same type, but it is so greatly altered that this determination may be incorrect.

Mineralogy of the Ores.—The primary minerals in the Engels vein are *bornite* and some *chalcopyrite*. Secondary *chalcocite* has developed in the upper part of the mine. At the Walker mine, the ore contains *bornite*, *chalcopyrite*, and silver-bearing *tetrahedrite*.

Mode of Occurrence of the Ores.—The ore body at the Engels mine is a lode, which has been traced for nearly 3 miles on the surface. The ore at the Walker mine is in a quartz vein.

Origin of the Ores.—The Engels mine deposit is regarded by some as being the result of a magmatic segregation and by others as having been formed by rising hot solutions that followed a shattered zone in the igneous rock. The origin of the deposit of the Walker mine is not given by those who have studied it, but it is evidently the result of deposition by solutions.

Production of the District.—The Plumas County district has been responsible for 0.51 per cent of the total production of the country. From 1865 to 1927, its output was 199,079,000 pounds of copper.

PIONEER, ARIZONA

The Pioneer district is in Pinal and Gila counties, Arizona. Copper has been produced in the district since 1904, but the real production began with the development of the Magma Copper Company's mine. The output from 1904 to 1927 was 183,887,000 pounds of copper, which was 0.47 per cent of the total production of the United States. The Pioneer ranks as the fifteenth copper district in the country.

Geology and Ores of the District.—The ore bodies of the Magma Company occur in a porphyry-filled fault fissure that cuts diabase, quartzite, and limestone. The ore is chiefly *chalcocite*, *chalcopyrite*, and *bornite*. All the ores carry silver and gold. The main ore shoot was 5 to 8 feet wide and 300 to 500 feet long near the surface, but at a depth of 2,000 feet it was nearly 22 feet wide and about 1,500 feet long. The ore averaged 8.56 per cent copper and 4.5 ounces of silver per ton. Recently, a body of ore containing lead and zinc was found on the 2,800-foot level, but it has not been developed as yet.

TINTIC, UTAH

The Tintic district lies in the north end of the Tintic Mountains in the northeastern corner of Juab County, Utah. Although it is primarily a silver camp, it has produced 0.45 per cent of the total copper production of the United States and ranks as the sixteenth district.

From 1880 to 1927, it produced 176,389,000 pounds of copper. It will be described more in detail under the discussion of silver.

Geology and Ores of the District.—A monzonite stock occurs in the area cutting Paleozoic limestones and other sediments. The solutions from the intrusive formed ore veins in the monzonite and replacement deposits in the limestone. The primary ores are complex. They yield silver, lead, zinc, gold, and copper. Some secondary enrichment of the copper has occurred, but much less than in most of the copper camps.

FOOTHILL BELT DISTRICT, CALIFORNIA

The Foothill Belt area extends (100 miles) northwest from Copperopolis in Calaveras County almost to Maryville in Yuba County, California. There are several small mining camps within the area, but the chief production comes from the mines of the Calaveras Company at Copperopolis. The district has been a small producer of copper since 1862, though during that time there have been periods of no production. It ranks as the seventeenth copper district in the United States and has produced a total of 172,211,000 pounds of copper, or 0.44 per cent of the copper production of the whole country.

Geology and Ores of the District.—The ore at Copperopolis consists mainly of *pyrite* and *chalcopyrite*, occurring in lenses of slates near intrusive igneous rocks. It is believed that the intrusives are related to the batholith of the Sierra Nevadas. Some oxidized ore was produced originally, but the production now comes mainly from the primary sulfides.

COPPER RIVER DISTRICT, ALASKA

An account of the copper deposits of the United States would not be complete without including a description of the very important Copper River district in Alaska. It is located on Copper and Chitna rivers in the Chugach Mountains. The mines are above the snow line, at an elevation of 6,000 feet, and are surrounded by glaciers.

Geology of the District.—The lower rocks of the area consist of basaltic lava flows, of uncertain age, which are now altered to greenstones (called the "Nikolai"). About 2,000 feet of Triassic dolomitic limestone rests upon the greenstones. All the formations dip to the east about 30°. Monzonite porphyries cut all the rocks, but their nearest outcrop to a copper deposit is 1.5 miles.

Mineralogy of the Ores.—The chief ore mineral of the district is *chalcocite*. Only small amounts of other copper minerals occur in the deposit.

Mode of Occurrence of the Ores.—The *chalcocite* occurs as tabular masses along a fractured zone in the limestone near its contact with the greenstones. The masses are not continuous for great distances but pinch out along the fractured zone. Their maximum sizes are 25 feet

in width and 400 feet in length. Small amounts of chalcocite occur in fissures in the greenstones, and, likewise in small amounts, it occurs disseminated throughout them.

Origin of the Ores.—Doubt exists as to the method by which this rich chalcocite ore was formed. Some geologists believe that moderately warm solutions from an igneous mass dissolved the copper out of the greenstones and redeposited it in the limestone. This seems unlikely, however, on account of the absence of any considerable deposits of chalcocite in the fissures of the greenstones, although it is so thoroughly disseminated through them. The disseminated ore is, moreover, undoubtedly later than the greenstone, as it occurs in the amygdules of the rock. A deposition by concentrated solutions of magmatic origin seems a more probable method of origin. Very little secondary enrichment (and that produced largely by oxidation) has occurred in the district, due to the character of the climate. There was considerable chalcocite in the talus below the outcrop of the deposit when it was first discovered.

The Production and Mines of the District.—Although the exact production figures are not revealed, the district produces between 50,000,000 and 70,000,000 pounds of copper annually. There are two large mines the Jumbo and the Bonanza, owned and operated by the Kennecott Mining Corporation. The ore produced in 1927 averaged 12.44 per cent of copper and 2.10 ounces of silver per ton.

PRINCE WILLIAM SOUND, ALASKA

A second important copper deposit in Alaska is that of the Beatson mine of the Kennecott Copper Corporation. It is located on Latouche Island in the southwestern part of Prince William Sound. In 1927, this mine produced 448,200 tons of ore averaging 1.57 per cent of copper.

Geology and Ores of the District.—The ores at the Beatson mine are replacement deposits along fractured zones in graywacke and slates.

They contain *pyrite*, *pyrrhotite*, *chalcopyrite*, and a little *sphalerite*. Quartz is the chief gangue mineral, but a little siderite and ankerite also occur.

OTHER COPPER DISTRICTS OF THE UNITED STATES

There are many other smaller districts in the United States that produce some copper ore. The most important of these are located on the map of copper districts, Fig. 56 (p. 157).

IMPORTANT FOREIGN COPPER DEPOSITS

Copper was produced by 36 countries in 1927. As it is impossible to describe all the deposits of these countries in this volume, only a general account will be given. The world map of copper deposits (Fig.

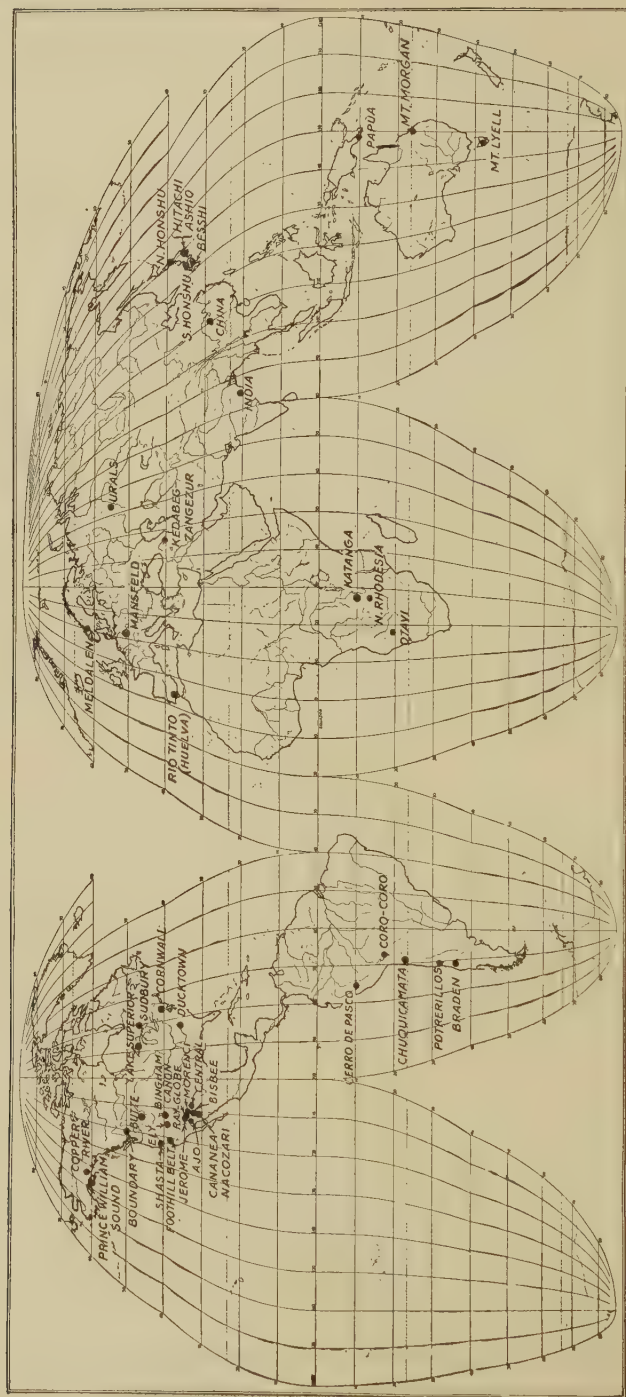


Fig. 66.—Important copper deposits of the world.

66) shows the distribution and location of the most important deposits. Besides the United States, which produced 50.60 per cent of the world's copper in 1927,¹ the leading countries and their percentage of the world production that year were as follows: Chile, 15.78 per cent; Belgian Congo (1926), 5.46 per cent; Japan, 4.17 per cent; Canada, 4.22 per cent; Mexico, 3.81 per cent; Spain and Portugal, 3.60 per cent; Peru, 3.13 per cent; and Germany, 1.87 per cent. Seventeen companies produced most of the foreign output of copper. The Chilean and Belgian Congo deposits are probably the largest in the world.

The Chilean Copper Deposits.—The estimated reserves of the Chilean copper deposits are between 400,000,000 and 600,000,000 tons of copper ore that averages from 1.5 to 3 per cent copper. One of these deposits, the Chuquicamata, is located in the desert of northern Chile and is owned by the Anaconda Copper Mining Company. It consists almost entirely of oxidized ore, mainly *brochantite* (copper sulfate) but some *atacamite* (copper chloride). *Chalcocite* and *covellite* are found in the deeper parts of the deposit. The brochantite has resulted from the oxidation of these two sulfides.

There are two other large and important deposits of copper in Chile. One belongs to the Braden Copper Company, and is located 50 miles southeast of Santiago; and the other to the Andes Copper Mining Company at Potrerillos, which is 100 miles east of Chanaral, in southern Atacama.

Copper Deposits of the Belgian Congo.—The other large foreign copper district is in Katanga in the southeastern corner of the Belgian Congo. The deposits are lenticular masses (many 300 feet wide and 3,000 feet long) occurring in slates, quartzites, and schistose rocks. They consist of high-grade, oxidized copper ore, which carries much cobalt. The deposits occur throughout an area about 100 miles in length and 30 to 60 miles wide. Important copper reserves occur in *Northern Rhodesia* just opposite the Katanga deposits, but as yet they are undeveloped.

Copper Deposits of Other Countries.—*Canada* has important copper deposits in the Trail and Boundary districts in British Columbia and at Rouyn district in Quebec.

In *Mexico*, the Cananea, Nacozari, and Boleo mines are the chief producers of copper.

The Cerro de Pasco mine in *Peru* is the chief copper mine of that country.

Europe has several copper deposits that make a fair production. The Rio Tinto and Tharsis mines in *Spain* and the Mason and Barry mines in *Portugal* contain the most important ones in the Spain-Portugal

¹ Julihn, C. E., U. S. Bur. Mines *Econ. Paper*, 1, 1928.

district. The Mansfeld shale (a thin bed of copper-bearing shale) is the chief domestic source in *Germany*.

Japan is the principal producer of copper in Asia, having furnished 99.5 per cent of Asia's total production since 1801. The following are that country's most important copper mines: Ashio, Bessi, Kosaka, and Hidachi. They are widely distributed over Japan.

The chief copper deposits of *Australia* are at Mount Lyell, Tasmania, and Mount Morgan, Queensland. Other smaller deposits occur on the continent.

USES OF COPPER

As noted in Chap. II, copper was the first metal used by man. It was later superseded by iron, which has maintained its supremacy for centuries. The supremacy of iron is now challenged, however, by copper, which has become an essential material in modern life. A little analysis of the objects of which one makes use during a day will reveal the fact that copper enters into innumerable phases of our daily life.

First among its uses are the electrical which, in the United States in 1928, required 540,600 tons, or about 45 per cent of the estimated total amount of copper used in the country. Automobile manufacturing required (exclusive of the electrical parts) 125,000 tons, which was 12.7 per cent of the total amount used. A rough division of the uses of copper into copper employed as the pure metal and as the alloy is as follows: pure copper (wire and rod, sheet, tube, and miscellaneous), 79 per cent; alloys of copper, 21 per cent.

The amount of copper consumed for the different uses in the United States is shown in the following table:

TABLE 36.—ESTIMATED AMOUNTS OF COPPER FOR ITS DIFFERENT USES IN THE UNITED STATES, 1928¹

Use	Amount, tons
Electrical manufactures.....	213,000
Telephones and telegraphs.....	119,000
Light and power lines.....	115,000
Trolley wire.....	6,300
Wire and rods.....	80,000
Wire cloth.....	6,500
Steam railways, electrified.....	800
Automobiles.....	125,000
Automobile brake lining.....	2,400
Buildings.....	62,000
Locomotives.....	1,100
Railway cars.....	3,200

¹ *Eng. and Min. Jour.*, vol., 127, p. 958, 1929.

TABLE 36.—ESTIMATED AMOUNTS OF COPPER FOR ITS DIFFERENT USES IN THE UNITED STATES, 1928 (*Continued*)

Use	Amount, tons
Air brakes.....	1,300
Ships, commercial.....	1,600
Ships, naval.....	300
Bearings and bushings.....	42,000
Valves and pipe fittings.....	20,500
Ammunition.....	8,200
Lubricators.....	5,000
Condensers.....	1,900
Fire-fighting apparatus.....	2,300
Agricultural machinery.....	1,500
Cash registers.....	400
Copper-bearing steel.....	1,600
Coinage.....	800
Radio receiving sets.....	5,100
Clocks and watches.....	4,600
Washing machines.....	4,200
Water heaters, household.....	2,600
Water meters.....	3,500
Refrigerators, electric.....	13,200
Plated ware.....	7,000
Safety razors.....	1,500
Radiators, heating.....	1,100
Other uses.....	50,000
Manufactures for export.....	65,600
Total.....	980,100

The use of copper in *alloys* has been known ever since the bronze age. Ancient bronze contained about 88 per cent copper and about 12 per cent tin. Today, bronze is largely what is known as "88-10-2," that is, copper, 88 per cent; tin, 10 per cent; and zinc, 2 per cent. When brass was first made is unknown. At present, brass represents a mixture of copper and zinc. It contains from 55 to nearly 100 per cent copper, the amount of zinc never exceeding 45 per cent. For making the common sheet and strip brass, a mixture of 63 to 70 per cent copper and the remainder zinc is used.

During recent years, copper alloys of many metals have been developed. Their physical properties are the deciding factors as to the use to which they are put. Prominent among these alloys are those with *nickel* and *aluminum* (aluminum bronze). Other metals that are being alloyed with copper are *cadmium*, *chromium*, *cobalt*, *silicon*, *lead*, *iron*, *beryllium*, *arsenic*, and *manganese*. A society in Philadelphia for testing materials has a list of hundreds of mixtures of copper with other metals.

The composition of a few common copper alloys is given in the following table:

TABLE 37.—COMPOSITION OF SOME COMMON COPPER ALLOYS¹

Name of alloy	Copper	Zinc	Tin	Nickel	Lead	Iron
Gilding.....	95	5				
Commercial bronze.....	90	10				
Bronze (88-10-2).....	88	2	10			
Rich low brass.....	85	15				
Low brass.....	80	20				
Admiralty brass.....	70	29	0.9			
Cartridge brass.....	66.5 to 69.5	30.38 to 33.38	...	...	0.07	0.05
High brass.....	64.5 to 67.5	32.15 to 35.15	...	...	0.30	0.05
Nickel silvers.....	55 to 70	15 to 25	...	30 to 5		
Forging brass.....	58.5 to 61.5	Remain- der	...	...	1.5 to 2.5	1.15
Manganese bronze.....	57 to 60	Remain- der	1.5	...	0.2	2.0 (MnO=0.3)

¹ *Mineral Industry*, p. 207, 1926.

The amount of copper consumed in the United States is enormous. In 1926, 1,570,000,000 pounds of new copper and 959,600,000 pounds of old (secondary) copper were used—enough to cover 104.4 acres with a layer a foot thick. The use of secondary copper recovered from old copper, scrap, and brass and other alloys is steadily increasing. In 1926, for every pound of new, 0.61 pound of old copper was used. The per capita consumption by the nations which lead in its use is of interest. The average for every person in the United States in 1926 was 15.54 pounds; in Great Britain, it was 6.86 pounds; in France, 6.23 pounds; and in Germany, 5.73 pounds.

PRODUCTION OF COPPER

The production figures for copper run into ten numerals, because this metal is marketed by the pound and all records are kept in pounds. The output in the United States in 1928 was the largest ever recorded and totaled 1,825,900,393 pounds. The leading copper-producing states were (in the order of production) Arizona (40 per cent), Utah (16.3 per cent), Montana (13.7 per cent), Michigan (9.8 per cent), Nevada (8.7 per cent), New Mexico, Alaska, California, Tennessee, and Colorado. One of the interesting recent developments is the production in 1928 of about 8,000,000 pounds of copper from Swain County, North Carolina. The yield by states in 1928 is shown graphically in Fig. 67. The percentage of the total copper production of the United States made by each state is shown in Fig. 68. The annual production for the United States from 1845 to 1928 is shown in Fig. 69.

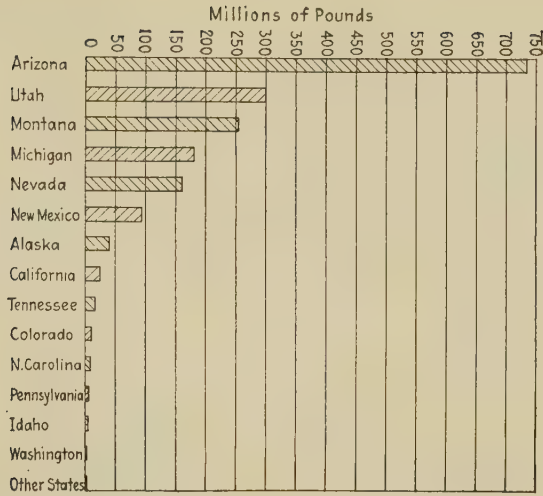


FIG. 67.—Production of copper in the United States, by states, in 1928. (Data from *U. S. Bur. Mines.*)

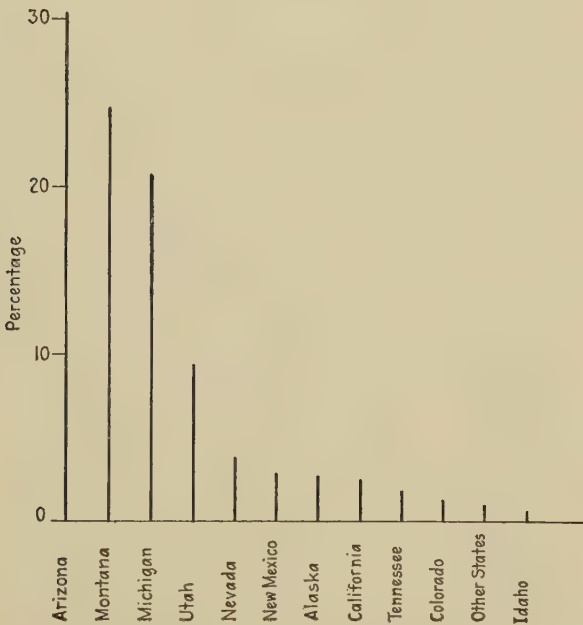


FIG. 68.—Percentage of total copper production of the United States from 1845 to 1926. (Data from *U. S. Bur. Mines Econ. Paper 1.*)

In point of world production of copper, the United States produced 56 per cent in 1927. The production of all continents and countries is shown in Fig. 70. The figure shows at a glance the leading producing countries and their percentage amounts. Since 1801, the United States has been responsible for 48.43 per cent of the world's total production.

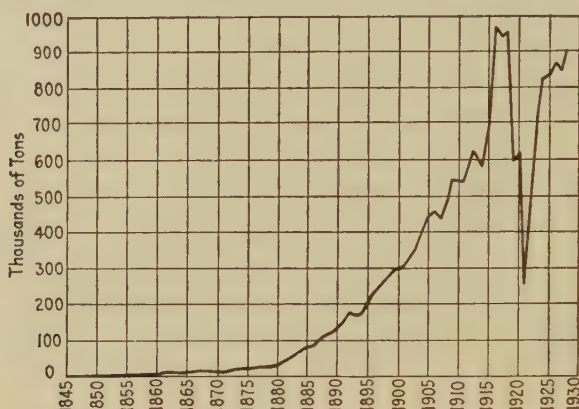


FIG. 69.—Annual smelter production of copper in the United States from 1845 to 1928. (Juliñ, *U. S. Bur. Mines Econ. Paper 1*, p. 16.)

TABLE 38.—FORECAST OF THE WORLD'S COPPER PRODUCTION, BASED ON YEARLY INCREASE OF 72,270 TONS (AVERAGE DAILY INCREASE, 198 TONS)¹

Year	Average production per day, short tons	Total production for the year, short tons
1926 (assumed)	4,372	1,595,780
1927	4,570	1,668,050
1928	4,768	1,740,320
1929	4,966	1,812,590
1930	5,164	1,884,860
1931	5,362	1,957,130
1932	5,560	2,029,400
1933	5,758	2,101,670
1934	5,956	2,173,940
1935	6,154	2,246,210
1936	6,352	2,318,480
1937	6,550	2,390,750
1938	6,748	2,463,020
1939	6,946	2,535,290
1940	7,144	2,607,560
1945	8,134	2,968,910
1950	9,124	3,330,260
2000	19,024	6,943,760

¹ JULIÑ, C. E., *U. S. Mineral Resources*, 1926, Part 1, p. 568.

The world output from 1881 to 1927 is shown in Fig. 71. Comparison with the production curve for the United States in Fig. 69 shows at once the control that the United States exercises over world production. This leadership has been declining slowly; and, as the quantities of copper from Chile and the Belgian Congo increase, it should continue to decline. Julihn¹ presents some interesting analyses of copper production and projects the study into the future. His analysis indicates that the world's copper production will increase tremendously in the future. One of his tables, based on the yearly rate of increase, is given on page 190.

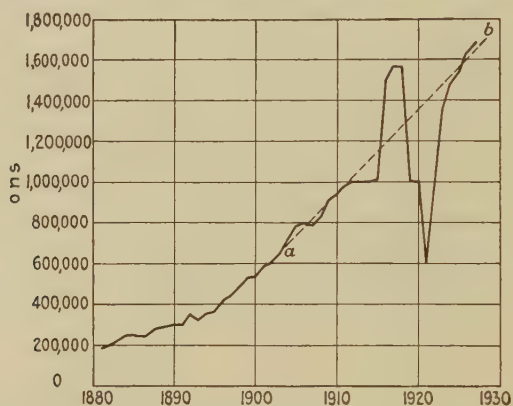


FIG. 71.—World production of copper from 1881 to 1927. Dotted line indicates the trend of world production. (Julihn, *U. S. Bur. Mines Econ. Paper 1*, p. 5.)

Julihn says that these figures are not to be taken as predictions but as showing where the present rate of copper output would lead. That such increases will ever take place is to be doubted. Many factors enter into the annual production, and in the future still others will be operative; for example, substitutes for copper and new methods of mining and extracting, to say nothing of unforeseen factors, some of which might decrease and others increase the need for copper. The question of the reserves of copper is a matter of some importance. At present, they are large and fully adequate, but each year a large amount is removed. One wonders how soon the use of secondary copper will equal or surpass the use of new copper.

Selected Readings on Copper

The literature on copper is voluminous, and it is difficult to select readings that are sufficiently general. The following references are given as an initial guide. The excellent bibliographies in many of the books and treatises listed here will enable the student to go farther if he so desires.

DAVIS, WATSON: "The Story of Copper," The Century Company, New York, 1924.
EMMONS, W. H.: "The Principles of Economic Geology," pp. 345-400, McGraw-Hill Book Company, Inc., New York, 1918. Contains a bibliography.

¹ JULIHN, *U. S. Mineral Resources*, 1926, Part 1, pp. 564-567.

- LEITH, C. K.: "Economic Aspects of Geology," pp. 197-209, Henry Holt & Company, New York, 1921.
- LINDGREN, WALDEMAR: "Mineral Deposits," McGraw-Hill Book Company, Inc., New York, 1928. Contains references and bibliographies throughout the book.
- PAINE, F. W.: Spurr's "Political and Commercial Geology," pp. 223-260, McGraw-Hill Book Company Inc., New York, 1920.
- RASTALL, R. H.: "Geology of the Metalliferous Deposits," pp. 228-259, Cambridge University Press, 1923.
- RIES, H.: "Economic Geology," pp. 568-620, John Wiley & Sons, Inc., New York, 1925. Has very complete bibliography.
- WEED, W. H.: "Copper Handbook," issued annually.
- U. S. Mineral Resources*, issued annually.
- Mineral Industry*, issued annually.

The United States Geological Survey has issued a very complete report on all the important copper-mining districts. The following is a partial list of these reports:

- Butte, Montana: W. H. Weed, *Prof. Paper* 74, 1912.
- Bingham Cañon, Utah: J. M. Boutwell, *Prof. Paper* 38, 1905.
- Bisbee, Arizona: F. L. Ransome, *Prof. Paper* 21, 1904.
- Ducktown, Tennessee: Emmons and Laney, *Prof. Paper* 139, 1926.
- Ely, Nevada: A. C. Spencer, *Prof. Paper* 96, 1917.
- Globe, Arizona: F. L. Ransome, *Prof. Paper* 12, 1903.
- Jerome, Arizona: Waldemar Lindgren, *Bull.* 782, 1926.
- Lake Superior: Van Hise and Leith, *Mon.* 52, 1911.
- Lake Superior: Butler and Burbank, *Prof. Paper* 144, 1929.
- Miami, Arizona: F. L. Ransome, *Prof. Paper* 115, 1919.
- Morenci-Metcalf, Arizona: Waldemar Lindgren, *Prof. Paper* 43, 1905.
- Ray, Arizona: F. L. Ransome, *Prof. Paper* 115, 1919.
- Santa Rita, New Mexico: Lindgren, Graton, and Gordon, *Prof. Paper* 68, 1910.
- Shasta County, California: Graton, L. C., *Bull.* 430, 1910.

A Few Important References

- EMMONS, W. H.: Sulfide Enrichment, U. S. Geol. Survey *Bull.* 625, 1917.
- JULIHN, C. E.: Summarized Data of Copper Production, U. S. Bur. Mines *Econ. Paper* 1, 1928.
- TOLMAN, C. F. JR.: Globe, Miami, and Ray, Arizona, *Min. and Sci. Press*, vol. 99, pp. 622, 646, 1909.

CHAPTER VII

LEAD AND ZINC

Lead and zinc have very dissimilar chemical and physical properties, as is shown by their wide separation in the periodic classification. Zinc is number 30 and has an atomic weight of 65.4, and lead is number 82 and has an atomic weight of 207.2. The two elements form compounds that are widely different in their solubilities, and yet the most common minerals of each are the sulfide and carbonate. Galena and sphalerite are the most common minerals of lead and zinc, so the same physical and chemical conditions must favor the formation of the sulfides of each of these metals, though just why this is so is not fully understood. In spite of their differences in chemical behavior, lead and zinc are associated in mineral deposits all over the world. In some deposits, their minerals are the dominant ones, as in the Tri-State zinc-lead district; in others, they are associated with those of copper, iron, and other metals. Because of this widespread association of lead and zinc in mineral deposits, it is advantageous to discuss them together.

Early History of Lead and Zinc.—Man has been familiar with metallic lead much longer than with metallic zinc. He used zinc, however, in compounds long before he was acquainted with the metal. Lead was extensively used by the Romans as a solder and for pipes, both of which uses have continued down to the present day. Zinc was used in brass by the Greeks but unwittingly, for they fused copper with zinc minerals to make the brass. Pliny speaks of a mineral, called “cadmia,” which, when mixed with copper, formed “aurichalcum.” He tells, also, of a deposit (really zinc oxide), formed in brass furnaces, that could be used with copper for the same purpose. The discovery of zinc as a metal in 1520 is credited to the German scientist Paracelsus. Another German scientist, Agricola, also discovered metallic zinc and described it in 1556. As late as 1702, cadmia was regarded as a metallic calx (residue) which, when mixed with copper, dyed the copper yellow by giving up its metal to it.

First Production of Lead and Zinc.—At the beginning of the nineteenth century, England was the world's leading producer of lead (the production in 1800 was 17,000 tons), and Spain was second (production, 10,000 tons). England continued to lead until the decade of 1850 to 1860, when Spain surpassed her. Spain reached her greatest yearly production of 258,000 tons in 1888 and was surpassed by the United States in 1891. The lead

production of the United States was moderate up to 1870, after which it mounted rapidly due to the great development of the western mines (Fig. 72). In 1927, the United States was responsible for about 37 per cent of the world's production of lead.

Zinc was produced in England after 1740 and on the continent after 1807, when production began at Liège, Belgium. Since 1801, the world's production of zinc has been confined largely to three countries:¹ Germany, Belgium, and the United States. For 110 years, Germany led the world

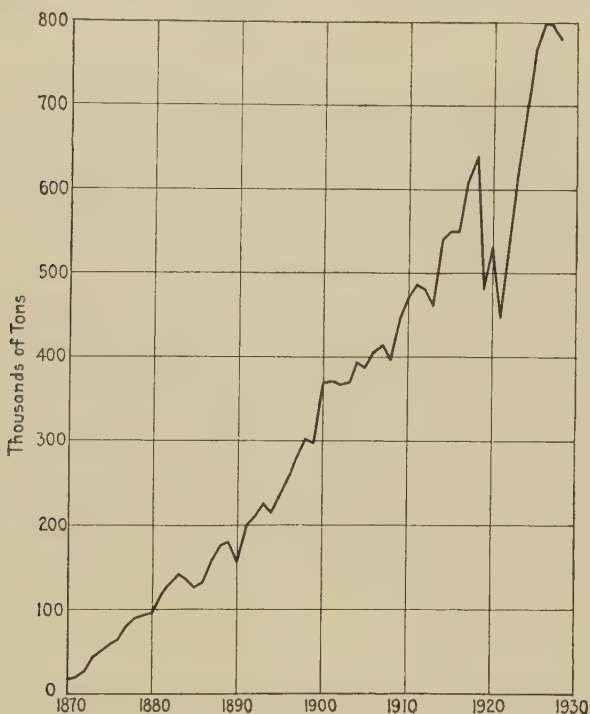


FIG. 72.—Annual lead production in the United States from 1870 to 1928. Note the uniform rate of increase in production. (Data from *U. S. Mineral Resources*.)

and was passed by the United States in 1909. During the nineteenth century, Germany produced about 43 per cent of the world's zinc, which came largely from the rich Silesian deposits. During the first decade of the nineteenth century, Great Britain had second place. She was responsible for 34.39 per cent of the world production of that period. Belgium was third with an output equalling 17.20 per cent of the world's total. Great Britain dropped to 14 per cent in the next decade, and Belgium went into second place, holding it until 1901, when it was obtained by the United States. From 1801 to 1900, Belgium was respon-

¹ PEHRSON, ELMER W., Summarized Data of Zinc Production, U. S. Bur. Mines *Econ. Paper*, 2, 1929. An excellent summary of the world production of zinc.

sible for 26.48 per cent of the world's zinc output for that period. The production of zinc in the United States began in 1858; and, although it was slow at first, it mounted rapidly after 1900 (see Fig. 73).

History of Lead and Zinc Mining in the United States.—The use of *lead* as bullets brought about its discovery in the United States long before any attention was paid to the zinc so often associated with it. The first discovery of lead in the country is believed to have been in the Mississippi Valley in 1701. Credit for the discovery goes to Le Seuer. The deposit was along the Mississippi River, somewhere in

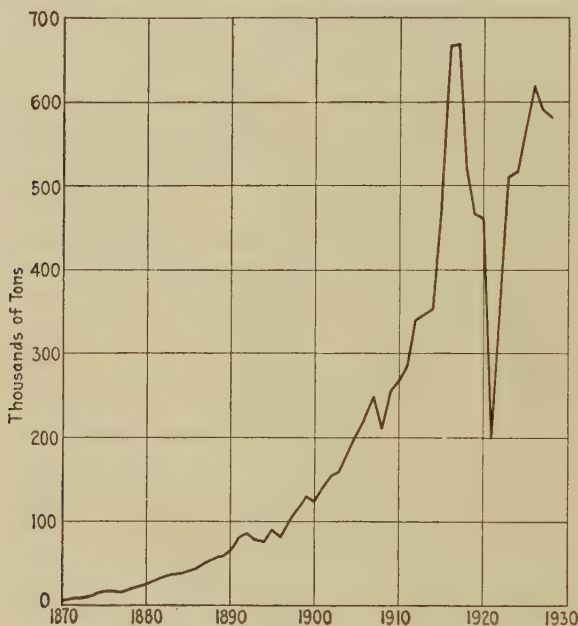


FIG. 73.—Annual zinc production in the United States from 1870 to 1928. Note the greater fluctuation as a result of the World War than is shown by lead in Fig. 72. (Data from *U. S. Mineral Resources*.)

the Wisconsin-Iowa area; but, so far as is known, no lead was mined from it.

The first discovery of lead about which much is known was in Madison County, southeastern Missouri, in 1720. A Frenchman, named Renault, had acquired a grant of land in Missouri from the French crown and equipped a party to go there to mine silver, which was reported to be abundant. A mineralogist, named La Motte, accompanied him and discovered the lead deposits. Although disappointed in not finding silver in the deposits, which are pure lead, they worked the lead from time to time but without much success.

The famous Austinville Mine, in Wythe County, Virginia, was found in 1750 by British army officers, and it furnished much lead for bullets

during the American Revolution. This mine contained zinc, also, and in later years was worked for it, though not during this early period. Moses Austin went from this mine in 1797 to the Missouri mines and erected a shot tower along the bluffs of the Mississippi River in order to utilize the lead from the nearby mines. A lead furnace was built and put into operation at the mines in Washington County, Missouri, in 1798 (see Fig. 74). Estimates by Schoolcraft credited this district with a production of 3,000,000 pounds of lead in 1819. The mining of these lead deposits was considerably stimulated when the United States acquired Louisiana in 1803.



FIG. 74.—A view in 1818 of Potosi (first named Mine à Burton), Washington County, Mo. Note the lead furnaces by curling smoke. The first lead furnace in Washington county was built in 1798. (Photograph of woodcut in H. R. Schoolcraft's "*The Lead Mines of Missouri*," 1819.)

The lead deposits of the upper Mississippi Valley are said to have been discovered by James Dubuque about 1788 (some reports state 1774) near the town in Iowa that bears his name. Regular mining in the Wisconsin-Iowa-Illinois area began in 1821, and the typical rush to the region of get-rich-quick promoters and miners followed. Production grew slowly, reaching a maximum for lead in 1845.

During the first quarter of the nineteenth century, lead deposits were discovered in Massachusetts; New York (worked from 1820 to 1854 and, possibly, in 1740, in Dutchess County); and Pennsylvania. Small deposits were located in other states during the period of 1826 to 1850, but none proved of value.

During the period of 1851 to 1875, the discovery and development of numerous deposits in the Mississippi Valley and the Rocky Mountain region took place. Though Leadville, Colorado, became a gold camp

in 1860, lead was not discovered there until 1875. The great disseminated lead deposits of St. Francois County in southeastern Missouri were found in 1869. Today, this district is the greatest lead-producing area in the world. The silver-lead deposits of Cœur d'Alene, Idaho, were first worked extensively in 1885.

Zinc has never been in the limelight in the United States, as have most of the other metals; and, although its occurrence in deposits worked for other metals must have been known, the first record of zinc production (20 tons) in the United States was made in 1858. The deposits at Franklin, New Jersey, were known as early as 1640, though they were probably not prospected for zinc at that time, but rather for the associated iron ore.

Brass was first made in the United States in 1802, but from imported zinc. Apparently, the zinc used for the next 60 years was imported, for the first metallic zinc made in the United States was in 1858.

Lead was discovered in the Tri-State area near Joplin, Missouri, in 1848; and zinc, in 1871. Other zinc deposits were found as the use of zinc in brass and for galvanizing was developed. At present (1928), the annual production of zinc in the United States is fourth in value among the metals.

Abundance of Lead and Zinc in Rocks.—It is known that small quantities (or, better, traces) of lead and zinc are found in many rocks. The presence of both metals has been detected in sea water and even in organisms of the sea. Zinc is found in the ashes of plants. The estimates made by Clarke and Washington for the amounts of lead and zinc present in igneous rocks are 0.004 per cent for zinc and 0.002 per cent for lead. Berg gives the amount of zinc as 0.006 per cent and of lead as 0.0008 per cent. The quantities of these metals obtained by analyses vary widely, but mere traces, only, are present in the majority of rocks.

Mineralogy of Lead and Zinc.—There are many minerals of lead and zinc, but the great majority of them are of no importance as sources of either metal. Only three minerals are important sources of lead and six of zinc. They are given in the following table:

TABLE 39.—COMMON LEAD AND ZINC MINERALS, WITH PERCENTAGE OF METAL IN EACH

Lead minerals	Percentage lead
Galena, PbS	86.6
Cerussite, $PbCO_3$	77.5
Anglesite, $PbSO_4$	68.3
Zinc minerals	Percentage zinc
Sphalerite, ZnS	67.0
Smithsonite, $ZnCO_3$	52.0
Hemimorphite, $2ZnO \cdot SiO_4 \cdot H_2O$	54.2
Zincite, ZnO	80.3
Willemite, Zn_2SiO_4	58.5
Franklinite, $(ZnMn)O \cdot (FeMn)_2O_3$	15.0 to 20.0

Physical Properties of the Lead and Zinc Minerals. Galena.—

Galena is the most abundant and the most widely distributed of all the lead minerals. It usually occurs in cubes, but it may be massive. It has excellent cubic cleavage. It is a pure lead-gray and has a bright metallic luster. Its hardness is 2.54, and its specific gravity is 7.4 to 7.6. Much galena contains silver, probably as silver sulfide, and some contains other metals, including native silver and gold.

Cerussite.—Cerussite is generally crystalline, usually having the form of elongated crystals many of which are in radiating clusters. It occurs, also, as grains and massive. Normally, cerussite is white or gray, but it may be other colors. It has a hardness of 3 to 3.5 and a specific gravity of about 6.5. Cerussite is far less common than galena and is found in the oxidized portion of a deposit.

Anglesite.—Anglesite occurs as flat crystals and massive. It is brittle. It is usually white but may be gray or yellowish. Its hardness is 2.75 to 3, and its specific gravity is 6.3. It is an alteration product of galena and is commonly pseudomorphic after it. Anglesite is found in oxidized deposits but is not an important source of lead.

Sphalerite.—Sphalerite is always crystalline, usually either as individual, rounded tetrahedrons or as large, crystalline, cleavable masses. Rarely, it is finely granular or has various shapes. Its cleavage is perfect and is dodecahedral (12-sided). It is the only mineral that has this cleavage well developed. It is commonly yellow, brown, red, black, and rarely nearly white. It always shows a resinous to brilliant luster. Sphalerite contains iron, manganese, and cadmium as impurities and rarely silver, gold, and the rare earths: indium, gallium, and thallium. It is by far the most common and valuable zinc mineral. It is found in a great number of mineral deposits, although not always in amounts that are large enough to mine.

Smithsonite.—Smithsonite is rarely found in good crystals; its most common forms are reniform, botryoidal, stalactitic, and less commonly granular masses. It is white, greenish, yellowish, or bluish. Its luster is vitreous to pearly. It has a hardness of 5 (the hardest of the common carbonates) and a specific gravity of 4.3 to 4.45. It is the most common of the oxidized zinc minerals and in some districts is an important source of zinc. It is often called "dry-bone" ore by the miners in allusion to its porous character.

Hemimorphite.—Most hemimorphite is crystalline. Small tabular forms are the most common, and they are usually in radiating aggregates; the crystals cover the surface of another mineral or line cavities. Hemimorphite occurs also in stalactitic, mammillary, and fibrous forms. It is white, yellowish, or brown and has a vitreous luster. Its hardness is 4.5 to 5, and its specific gravity is 3.4 to 3.5. Hemimorphite forms in

the oxidized zone where there is silica. It is not so abundant as the carbonate. Hemimorphite was formerly called "calamine."

Zincite.—Zincite is rarely found as distinct crystals but rather as coarsely crystalline, cleavable masses and as grains. Its color, which is very distinctive, is deep red shading to orange-yellow. Its streak is orange-yellow. The hardness of zincite is 4 to 4.5, and its specific gravity is 5.43 to 5.7. Zincite occurs only at Franklin and Sterling Hill, New Jersey, where it is associated with willemite and franklinite.

Willemite.—Willemite is generally massive but may occur as prismatic crystals. If pure, it is white or greenish-yellow. It may also be apple-green, flesh-red, grayish, or even brown. Its luster is vitreous to resinous. The hardness of willemite is 5.5, and the specific gravity, 3.89 to 4.18. Willemite nearly always contains a little iron and manganese. It is found with zincite and franklinite in New Jersey but occurs in zinc deposits in other places, also.

Franklinite.—Franklinite may occur in well-developed crystals, but usually it is in rounded crystals or massive, granular masses. It is black and has a conchoidal to uneven fracture. Its hardness is 5.5 to 6.5, and its specific gravity is 5.07 to 5.22. It is slightly magnetic. Although often cited as containing ferrous iron, franklinite rarely contains it. It is an important source of zinc (as are also zincite and willemite) in the deposits at Franklin, New Jersey. Franklinite is not found elsewhere in the United States.

Composition of Lead and Zinc Deposits.—As already noted, lead may occur without zinc, and *vice versa*, but usually the two are found together. Probably, the great majority of lead and zinc deposits contain *galena* and *sphalerite* as their chief minerals. The former occurs without zinc in the southeastern-Missouri "lead belt," and the sphalerite deposits of eastern Tennessee contain only a very little galena.

Where lead and zinc occur together, galena and sphalerite may be the chief minerals in the deposit, as in those of the Oklahoma-Kansas-Missouri district and the upper Mississippi Valley district of Wisconsin, Illinois, and Iowa. Throughout western United States, however, complex ores carrying sphalerite, galena, pyrite, chalcopyrite, pyrrhotite, and various other sulfides are the rule. Such deposits nearly always carry values of gold and silver.

Where oxidation has occurred, as in western and southwestern United States, *smithsonite* and *hemimorphite* (the common oxidized zinc minerals) have developed in considerable abundance. *Cerussite* (lead carbonate) occasionally develops in these oxidized deposits, but its formation requires a long time and favorable chemical conditions because of the great insolubility and stability of galena from which it must form.

Lead commonly occurs with silver. Very important deposits of *argentiferous galena* are known; those of the Cœur d'Alene district in

Idaho are notable examples. In this district, zinc is abundant in some of the mines, but it does not occur in the principal lead-silver deposits.

Zinc occurs entirely alone in the remarkable deposits at Franklin, New Jersey. In these, the three zinc minerals, *zincite*, *willemite*, and *franklinite*, are intimately intergrown and constitute the ore. This is the only deposit of its kind in the world.

Copper, lead, and zinc in varying amounts are associated in the deposits of many districts. Formerly, zinc was regarded as a nuisance in smelting the complex ores in which it occurs, and mining companies were penalized for amounts of it above 10 per cent. Due to the progress made in metallurgical practice in recent years, however, all the metals are now saved.

Secondary Enrichment of Lead and Zinc Deposits.—All lead minerals are very insoluble. Galena is slowly attacked by waters containing oxygen or carbon dioxide and is converted into the sulfate or carbonate. In the presence of an abundance of carbon dioxide, the carbonate (which is the most insoluble lead mineral) forms from the sulfate. It is the presence of these two insoluble minerals as a thin coating on galena that aids in preventing the galena from being dissolved and accounts for the slightly rounded form of galena crystals in residual deposits.

Because of the insolubility of lead compounds, they are never transported far by solutions but form residual deposits, either of galena or of the oxidized minerals. This insolubility also prevents the secondary sulfide enrichment of galena, and no positive proof of its redeposition as the sulfide has been found.

Sphalerite is readily altered to zinc sulfate, which, being soluble in water, can be carried downward by ground water or removed by streams. As a result, many zinc deposits show a zone of oxidized minerals, such as smithsonite (especially in limestone) and hemimorphite (where silica is available). Strangely enough, deposits containing smithsonite are less common than one would expect. The districts of Joplin, Missouri, and Leadville, Colorado, produce considerable amounts of hemimorphite.

Sphalerite could be formed in the sulfide-enrichment zone, but there is little evidence that it has been formed there.

Gangue Minerals.—The carbonates, calcite, dolomite, siderite, and rhodochrosite, are very common gangue minerals in both lead and zinc deposits. Others are barite, fluorite, quartz, chert (also called "jasperoid"), and marcasite and other sulfides.

Types of Lead-zinc Ores.—The ores of lead and zinc are generally known from the chief constituents by such names as "lead-zinc," "copper-lead," "zinc-copper," and "lead-silver" ores. Probably not so many different types of lead and zinc ores are worked as of copper ores.

Tenor of Lead and Zinc Ores.—The amount of *lead* an ore must contain to make it profitable to mine depends upon many factors.

Market value, cost of mining and treatment, and nearness to market are some of these. If silver is present in an ore, the percentage of lead can be less. Very large tonnages of low-grade ore sometimes make it possible to produce lead at a lower cost per pound than that at which a higher-grade ore can be produced. This is because the large tonnages make it possible to use very cheap mining methods.

The average metallic content of the Cœur d'Alene lead-silver ore in 1927 was 8.41 per cent lead, 0.03 per cent copper, 4.29 ounces of silver, and a little zinc per ton. The lead ore mined in Arizona in 1926 averaged 6.17 per cent lead, 4.54 ounces of silver, 0.067 ounce of gold, and a little copper per ton. In contrast to these ores, that of the Southeastern Missouri district, which produces only lead, contained in 1927 an average of 3.17 per cent of metallic lead.

Zinc is equally variable in amount in different ores. That found in Utah occurs largely with the lead. The average tenor of these ores in 1926 was 3.90 per cent zinc, 6.47 per cent lead, 0.21 per cent copper, 6.07 ounces of silver, and 0.03 ounce of gold per ton. The average amounts of zinc and lead in the ores of Oklahoma (the state leading in the production of zinc) in 1927 were 2.36 per cent zinc and 0.53 per cent lead. The ore mined in Wisconsin, the same year, yielded 2.79 per cent zinc and 0.14 per cent lead. These very low-grade ores are concentrated before smelting, just as low-grade copper ores are.

Impurities of Lead and Zinc Ores.—Lead and zinc ores always contain small quantities of other metals. Lead may contain silver, gold, antimony, arsenic, and copper; and zinc may contain cadmium, iron, copper, silver, and gold. Very minor quantities of other elements are found in the metals from certain districts. The small quantities of many of these substances present in lead and zinc do not affect them for most of their uses. Most lead contains sufficient silver to pay for its recovery. Lead that is almost free from silver is known as "soft lead." (The ores of the Mississippi Valley are soft-lead ores.) A little arsenic in lead improves it for shot making. The cadmium in zinc is more volatile than the zinc and thus passes off first and is saved.

Treatment of Lead and Zinc Ores.—The successive steps in the treatment of lead and zinc ores, *i.e.*, *mining*, *concentration*, and *smelting*, are essentially the same as for the metals previously discussed.

Mining.—Practically all lead and zinc ores are obtained by underground mining methods. During the early periods of lead mining, much galena was recovered from open pits, where it had been concentrated in the residual soils. It is stated that the Sac and Fox Indians in the vicinity of Prairie du Chien, Wisconsin, mined 250 tons of galena with a hoe during the early days of mining in that region.

Many lead and zinc deposits are irregular, and the mining method must always be adapted to the mode of occurrence of the ore. In

southeastern Missouri, where the ores are of low grade, the room-and-pillar method of mining is used. The pillars support the top (Fig. 75), and many are 75 feet high, showing what large quantities of ore are removed. Electric shovels are used, and thousands of tons of ore are handled daily.

Concentration.—The high specific gravity of *galena* makes it easy to concentrate by water, provided it occurs alone. Jigs and tables are used for this purpose. Galena is brittle, however, and, therefore, large amounts of a very fine powder of the mineral are produced during grinding. This fine powder floats on water, as do the powders of all sulfides,



FIG. 75.—View in a lead mine in the Southeastern Missouri district, showing the pillars left to support the roof. The picture gives a good idea as to the amount of material removed.

because they are not readily wet by water. The powdered sulfides easily unite with a drop of oil, however, and so are saved by the oil-flotation method. This method of concentration has saved hundreds of millions of dollars since it was invented, about the beginning of the present century.

Zinc minerals, especially *sphalerite*, are not so easily concentrated as galena, because their specific gravities are nearer to those of some of the other sulfides and gangue minerals. Inasmuch as the major part of all zinc ores are complex sulfide aggregates, most zinc ores are finely ground and two or three concentration products are made. These are (1) lead (and some zinc), (2) zinc (and some lead), and (3) an iron product (pyrite, for example). Oil flotation is the chief method used. The

material concentrated is very fine, 90 per cent of it going through a 200-mesh screen.

Smelting.—The smelting practices for lead and zinc are very different. The *lead* concentrate can be treated by different methods for lead recovery. A common method is to charge from 1 to 4 tons of concentrate into a reverberatory furnace the doors of which are left open. The charge is roasted from 2 to 4 hours, and a mixture of PbS, PbO, and PbSO₄ is produced. The furnace is then closed and the temperature raised, whereupon a reaction takes place by which metallic lead is formed. The lead settles to the bottom of the furnace and is drawn off in ladles. If copper is present in the ores, it rises to the surface of the molten lead and is skimmed off. Silver, which is generally present, may be removed by electrolytic or other methods.

Zinc may be recovered from its ores by volatilizing and then condensing it or by dissolving it out of its ores and precipitating it electrolytically. Unless the ore is an oxidized one, such as hemimorphite, smithsonite, or the New Jersey ores, the concentrate is roasted to burn off the sulfur (used in some plants to make sulfuric acid) and oxidize the ore.

If the *volatilization method* is used, the roasted ore is put into retorts (between 4 and 4.5 feet long and from 7.5 to 8.5 inches in diameter) and heated from the outside. The zinc volatilizes and passes out of the retort into a condenser, where it condenses as liquid zinc and is drawn off.

By the *electrolytic method*, the zinc is dissolved in sulfuric acid; the resulting solution is purified to remove copper and cadmium; and the zinc is then deposited on aluminum sheets by an electric current. The metallic zinc is stripped from the aluminum, melted, and cast into slabs, which weigh about 50 pounds and are 99.9 per cent pure.

MODE OF OCCURRENCE OF LEAD AND ZINC ORES

Lead and zinc deposits are of four types: (1) *residual* deposits (dominantly of lead but also of zinc), (2) *vein deposits*, (3) *replacement deposits*, and (4) *disseminated deposits*. In some districts, one type of deposit predominates; and in others, two or more types may be present in practically equal amounts. Where there are two or more kinds of deposits present, one grades into another. The majority of lead and zinc deposits occur in sedimentary rocks, especially limestones and dolomites.

Residual Deposits.—Galena, being very insoluble in meteoric waters, remains behind as the other materials are removed. The limestones and dolomites, in which lead and zinc ores commonly occur, are soluble; and, as they are removed, the galena is concentrated in the residual soils. Undoubtedly, the majority of lead and zinc deposits were discovered on account of these deposits of residual galena right at the surface (another reason for the early discovery of lead). A little oxidation has

occurred in some residual deposits of galena but only rarely enough to have produced oxidized minerals in amounts that are economically important. Oxidized zinc minerals may occur with the residual galena; but, as a rule, because the zinc is far more soluble, it is carried below and redeposited, commonly as a replacement deposit of oxidized minerals.

Vein Deposits.—Well-defined vein deposits of lead and zinc, either of the filled-fissure type or (as is probably more common) the replacement-vein type, are of fairly widespread occurrence. Many vein deposits of lead and zinc occur in western United States. In the upper Mississippi Valley, southern Illinois, and eastern Tennessee, veins of lead and zinc occur, also, though in some of these districts, replacement deposits have been formed along the walls of veins.

Replacement Deposits.—The widespread occurrence of lead and zinc deposits in limestones and dolomites is due to the ease with which these two rocks are replaced by solutions. The ore-bearing solutions, being hot and excellent solvents, pass outward from the magma into an adjacent limestone or dolomite and replace parts of it by the lead and zinc minerals. Some of the deposits of these ores follow the structural position of the replaced beds and are then known as “bedded veins” or “bedded deposits.”

Disseminated Deposits.—Disseminated ores of lead and zinc form very important deposits. They occur almost entirely in limestones and dolomites. The ore minerals are sparsely scattered through the rock, representing in many deposits only 3 or 4 per cent of the rock. The minerals occur as isolated grains, as thin veinlets, and in cavities in the rock. The lead deposits of southeastern Missouri are excellent examples of this type of deposit.

In some of the disseminated lead and zinc deposits, complexity in minerals is the rule. Sphalerite, galena, chalcopyrite, pyrite, and other sulfides (to say nothing of calcite, dolomite, quartz, barite, and a few other gangue minerals) are intimately intergrown. Such ores are difficult to treat; but if the values are high enough, it can be done.

PRINCIPAL LEAD AND ZINC DISTRICTS OF THE UNITED STATES

Only a few of the important lead and zinc deposits consist exclusively of one metal, though in the majority of deposits one or the other of the metals predominates in amount. The districts will be discussed under the designation of the metal dominant in them. The distribution of the lead and zinc deposits in the United States is shown on the map of Fig. 76.

LEAD DISTRICTS

Districts that produce lead alone are very few. The lead-silver districts will be included here with the “lead districts” if the total lead value of the ores exceeds the silver value, as it does in the Cœur d’Alene district.

SOUTHEASTERN MISSOURI

The Southeastern Missouri district (frequently called the "lead belt") contains the most important deposits of lead in the world. In 1928, the lead production of this district was greater than that of any foreign country. The deposits are located chiefly in St. Francois County, at Bonneterre, Flat River, and Elvins, though important deposits also occur at Annapolis in Iron County and at Mine La Motte in Madison County. Some small deposits occur in Washington County, where, during the productive period of 1800 to 1840, most of the lead produced in the district was mined. (See Fig. 77.) The disseminated ores, lying

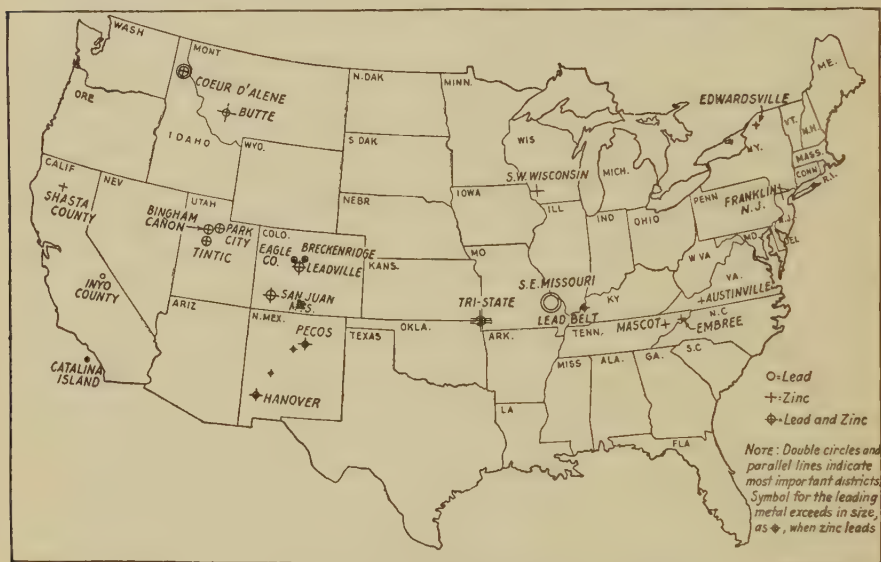


FIG. 76.—Lead and zinc deposits of the United States.

from 100 to 600 feet below the surface, were discovered by deep drilling in 1869; and their subsequent development, though slow at first, has been tremendous during the last 30 years. The famous old Mine La Motte, where lead was discovered in 1720, is in this district.

Geology of the District.—The geology of the Southeastern Missouri district is very simple. The important country rock is the Bonneterre dolomite (Cambrian), which contains in its lower part some thin, lenticular shaly beds. Beneath the dolomite lies the La Motte sandstone (also Cambrian), which rests on pre-Cambrian igneous rocks, and above it is the Davis shale of Cambrian age. The formations are nearly flat throughout the area. Small faults of a few feet displacement are common, and there are a few major faults representing movements as great as 700 feet.

Mineralogy of the Ores.—The only important mineral in the deposits is *galena*, which, in the disseminated deposits, is in crystals up to $\frac{1}{2}$ inch across and, in cavities, occurs as larger, well-formed crystals. The chief gangue minerals are dolomite (both as the constituent of the country rock and as crystals in the cavities), calcite, and glauconite (erroneously determined as chlorite by Buckley and usually quoted as such). Certain parts of the ore body contain small amounts of pyrite, chalcopyrite, and sphalerite. About 1 ounce of silver per ton is present in the ores. It occurs largely in the sphalerite, only traces being present in the galena, which is, consequently, "soft lead." In Madison and Washington counties, a little cerussite was formed from the galena but not in sufficient quantities to be economically valuable.

In the mines of Madison County, a deposit of cobalt-nickel-copper ore is associated with the lead ore. The galena occurs in the base of the Bonneterre dolomite, and the cobalt-nickel-copper ores are in the top of the La Motte sandstone. The latter contain linnæite as the source of the cobalt and nickel, and chalcopyrite as the source of the copper. A little sphalerite is present in these ores, also. Linnæite and chalcopyrite have been found likewise in certain parts of the mines of St. Francois County by the author of this volume.

Mode of Occurrence of the Ores.—

The deposits of the district are dominantly disseminated ores in dolomite. Vein deposits occur, but they are relatively unimportant in amount. Both disseminated and vein deposits occur in Washington County, though neither is very productive. The ore bodies are flat lying and in some mines are over 100 feet thick. Their horizontal extent is extremely variable, and so is the distribution of the ores within a given ore body, some parts of the mass being very rich and others lean.

Origin of the Ores.—The lead deposits of the Southeastern Missouri district, occurring as they do without association with igneous rocks other than the pre-Cambrian, have long been regarded as ideal illustrations of deposits formed by meteoric waters. Their description and explanation have been attempted, however, by only a few investigators.

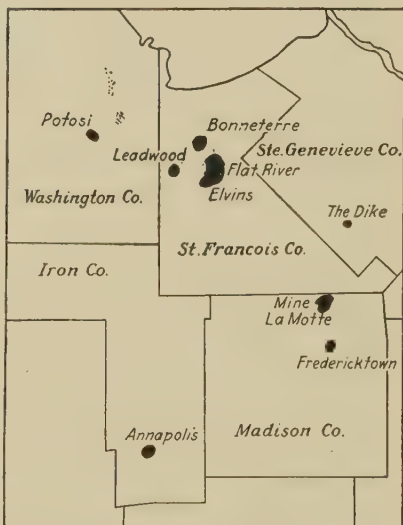


FIG. 77.—Map of southeastern Missouri showing the location of the lead deposits.

The author of this volume¹ many years ago came to the conclusion that these lead deposits were formed by waters of igneous origin, coming probably from an intrusive mass at a considerable depth, the solutions having risen along fracture zones in the underlying, pre-Cambrian igneous rocks. On reaching the sedimentary rocks, the solutions spread out and deposited minor amounts of the lead in the La Motte sandstone (first reached, of course) but the major part in the base of the more easily replaceable dolomite just above it. The dolomite was a much-fractured rock, which is proved by the large number of thin veinlets of galena present in it. These fractures aided in the formation of the disseminated deposits.

It has been proved that only hot solutions are able to transport large amounts of the difficultly soluble lead salts. That meteoric waters cannot do so is proved by the prevalent residual deposits of galena showing a minimum effect of solvent action. To talk, therefore, of galena's being dissolved out of rocks by cold meteoric waters and transported by them, as supporters of the theory of the meteoric origin do, is inconsistent with the facts.

The deposits might possibly, though not very probably, be explained on the basis of a zonal arrangement of metals. According, however, to the outline of the formation of ore deposits given in Chap. III of this volume, the lead-bearing solutions could have come from a magma that was free from other metals; or, if other metals were present, they could have been deposited first and be below the galena, or they could have been deposited above the galena and have been eroded away. There is no reason for believing that lead might not have been the only metal in the solution, as we have evidence in many ore deposits that only one metal was dominant in the solutions forming them. If objection to a theory of magmatic origin for these deposits be made on a basis of the distance the solutions would have had to travel (this distance, being unknown, may have been small), it can be confuted by the abundance of sound evidence that solutions have formed ore deposits 1,000, 3,000, and even 10,000 feet from the source magma.

Further support for the view of a magmatic origin for the lead is obtained from the fact that a few miles southeast of the deposits a dike of peridotite, accompanied by small veins of lead, zinc, and iron sulfides, occurs cutting the Cambrian rocks. Undoubtedly, some movement of igneous material below has occurred in the region since Cambrian times. To the south of the ore deposits, veins of both lead and zinc cut the pre-Cambrian rocks.

¹ A detailed discussion of the origin of these deposits is impossible here, but the author has in preparation a paper on this subject giving in detail the data bearing on a magmatic origin of the deposits.

Production and Mining in the District.—The Southeastern Missouri district furnishes yearly about one-third of the lead produced in the United States. In 1928, 6,292,500 tons of ore that contained 3.17 per cent of lead was mined and treated. A very small production of silver and zinc is also made. The use of electric shovels in the large stopes makes possible the mining of the large tonnages of ore. Prospecting for new ore bodies and the determination of the size of an ore body are accomplished by diamond drilling.

CŒUR D'ALENE, IDAHO

The Cœur d'Alene lead-silver district is on the western slope of the Cœur d'Alene Mountains in Shoshone County, northern Idaho. It lies near the boundary line between Idaho and Montana. The district has been an important one since 1885.

Geology of the Area.—The rocks of the area consist of a great thickness (between 17,000 and 18,000 feet) of metamorphosed pre-Cambrian sediments, dominantly quartzites and slates. Much folding has occurred, during which the original sediments were altered to their present state. Faults are common. Monzonite and monzonite porphyry occur intrusive in the pre-Cambrian rocks, and well-marked contact-metamorphic zones are present.

Mineralogy of the Ores.—*Galena* (*silver bearing*) is the chief mineral of the lead-silver ores. It is accompanied by a little pyrite, sphalerite, and silver-bearing tetrahedrite. The chief gangue minerals are siderite and quartz. The recently developed zinc ores have the same mineralogy, except that sphalerite is the most abundant mineral.

Mode of Occurrence of the Ores.—The lead-silver ores occur as lodes in quartzites. The deposits have the same general trend as the faults of the area. The vertical range of the ores has been shown by mining to be over 4,600 feet. Some parts of the lodes are 40 feet wide, but they average 9 feet. Some of the lodes, as those of the Bunker Hill and Sullivan mine, are over 7,000 feet long. The ores in these great lodes have essentially the same values at the bottom as at the top. The zinc ores occur in the same type of lode deposit as the lead-silver ores.

Origin of the Ores.—Those who have studied the deposits of the district believe that the ores are connected in origin with the monzonite intrusives, although the nearest outcrops of the monzonite are several miles from the lead-silver ores. The hot ore-bearing solutions from the magma developed, of course, both the contact-metamorphic zone near the monzonite and the lodes at a greater distance from it. Siderite was the first mineral deposited. It was a replacement of quartzite. Galena was later deposited both as a replacement of some of the siderite and as a replacement of quartzite.

Production.—The Cœur d'Alene district produced 22 per cent of the lead production of the United States in 1928, ranking as the second lead district. The lead-silver ore mined in 1927 averaged 10.4 per cent lead and 3.8 ounces of silver per ton. The district ranked third in the United States in the production of silver in 1927. The zinc ores are found in the mines of the eastern and the extreme southwestern parts of the area.

LEAD DISTRICTS OF UTAH

Utah ranked third in the production of lead in the United States in 1928. The lead comes dominantly from three districts: Bingham Cañon, Park City, and Tintic.

The *Bingham Cañon* area has been discussed under Copper, but it should be noted that, while the district in 1928 produced about 282,000,000 pounds of copper, it produced 100,000,000 pounds of lead and 47,000,000 pounds of zinc. It is, therefore, not only a very important copper producer but an important lead and zinc district, also.

The lead-zinc-silver ores at Bingham Cañon are in the limestones, not far from the porphyry. They occur as veins and replacement deposits but were formed at a lower temperature than the contact-metamorphic deposits. They consist of *galena*, *sphalerite*, *pyrite*, and *chalcopyrite*. The chief mines containing these ores in 1928 were the Utah-Delaware, Utah-Apex, and Bingham.

The *Park City district* produced in 1928 approximately 86,000,000 pounds of lead and 48,000,000 pounds of zinc; and the *Tintic district*, about 82,000,000 pounds of lead and 48,000 pounds of zinc. These two areas are described as silver camps under Silver (p. 261); and, as the lead and zinc deposits are identical with the silver deposits, they are described there, also.

OTHER LEAD DISTRICTS

Lead is produced in Colorado (from several areas), Montana, Arizona, and Nevada; but in all these states it is taken from ores that are much richer in other metals, especially silver, and, therefore, the description of the deposits is given under the head of the dominant mineral.

ZINC DISTRICTS

Mining districts that produce dominantly zinc are more numerous than those for lead, though deposits of zinc, alone, are also rare. Zinc deposits are more widely distributed in the United States than lead deposits (Fig. 76, p. 206). In 1927, 11 states produced more than 10,000 tons of zinc, while only 6 produced more than 10,000 tons of lead.

TRI-STATE (OKLAHOMA-KANSAS-MISSOURI) DISTRICT

The Tri-State district is the largest producer of zinc in the world at present (1928), and a remarkable thing about this great production is that it is made by mining and treating zinc and lead ores that are of a lower grade than any others in the world. The district is located where the three states, Oklahoma, Kansas, and Missouri, join. The Tri-State area really consists of three districts; one centering about Joplin, Missouri, and extending from Duenweg and Webb City, Missouri, on the east to Galena, Kansas, on the west; another surrounding Quapaw, Miami, and Picher, Oklahoma, and extending northward to Baxter Springs, Kansas; and a third about Granby, Missouri (Fig. 78).

Geology of the Area.—The geology of the Tri-State area is simple. The ores are found in the Boone formation (Mississippian). The rocks dip slightly to the northwest. In the Oklahoma-Kansas area, Pennsylvanian shales rest on Mississippian beds and also occur in patches in the Missouri area. Two prominent faults of small displacement occur in the district. One is the Seneca fault in Missouri and Oklahoma, and the other is the Miami fault in Oklahoma and Kansas. The former is mineralized, and considerable prospecting is being done along it. There is a marked unconformity between the Mississippian and Pennsylvanian formations. The Mississippian land surface had been strongly dissected, and a widespread system of underground drainage channels developed. The development of sink holes in connection with the underground drainage gave rise to a typical karst topography. Apparently, strong drainage channels were developed along the Grand Falls chert member, probably in connection with those higher up. Residual chert collected on this old land surface and now forms conglomeratic beds at the contact of the Pennsylvanian and Mississippian formations.

Mineralogy of the Ores.—*Sphalerite* and *galena* are the chief ore minerals. They are accompanied by a little chalcopyrite, pyrite, and marcasite. The galena carries only a trace of silver. The sphalerite contains cadmium sulfide, which appears also as an amorphous yellow coating on the outside of the ore. The gangue minerals are chert, jasperoid (a dark chert), quartz, dolomite (very abundant), calcite, and a little barite.

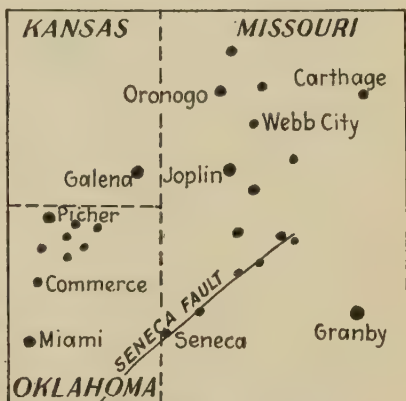


FIG. 78.—Sketch map of the Tri-State zinc-lead district. Black dots show the distribution of the mines.

The mineralogy in the Granby area is interesting because the chief mineral is *hemimorphite*. It is accompanied by some *smithsonite*. Both these minerals are secondary in character, as they occur replacing sphalerite.

Mode of Occurrence of the Ores.—The zinc-lead ores occur in two common forms: (1) as *runs* and *circles* in broken ground near the surface and (2) as *sheet* or *blanket* ore along essentially the same horizon in the Grand Falls chert. There are also minor occurrences of disseminated ores in the limestone below the Grand Falls chert, and one or two ore horizons have been found by drilling to the deeper formations.

The *runs* and *circles* (Fig. 79) produce most of the ore. The *runs* developed in solution channels that followed cherty horizons in the



FIG. 79.—Sketch map showing circles and runs near Joplin, Montana. Stippled areas represent shale in sink holes. (U. S. Geol. Survey, Folio 148.)

limestones. The removal of the limestone around the chert nodules caused the settling and brecciation of the chert and the fissuring of the adjacent limestone. The runs range from 10 to 300 feet in width, have a maximum vertical extent of 80 feet, and a maximum length of 2 miles. Essentially all of them are within 250 feet of the surface. The *circles* are associated with the numerous sink holes of the area. Chert has accumulated along the walls and bottoms of the sink holes, and shale (Pennsylvanian) fills the central parts. Some of these sink holes are deep enough to reach the Grand Falls chert; others are shallower and are connected with runs. One of the largest of these circles, the Oronogo, was 800 by 650 by 200 feet. It extended down to the sheet ground of the Grand Falls chert. Other circles are 100 feet across and much shallower. The ore is confined to the chert around the sink hole

and in some deposits is 25 to 30 feet thick. The broken chert masses, having furnished open spaces for the circulation of solutions, now contain the ore minerals in all their modes of occurrence. The minerals were deposited on the chert fragments; and, in places, they completely fill the openings, cementing the chert together.

The *sheet ground* occurs in the Grand Falls chert. It was formed, like the runs, by the removal of the limestone around the nodules of chert; but it is confined rather definitely to one horizon. It averages between 5 and 15 feet in thickness but locally may be much thicker. The ores of the sheet ground are not so valuable as those of the runs and have been developed only to a limited extent in Oklahoma and Kansas. The ores occur in the same manner as those of the runs and circles.

Origin of the Ores.—The ores of the Tri-State area are believed to have been deposited by rising solutions that had their source in an intrusive mass below. This mass was close to, if not actually in, the deeper-lying dolomitic members of the Paleozoic formations, as is shown by the abundant occurrence of dolomite as a gangue mineral. The ore-bearing solutions were rich in the elements necessary for the formation of dolomite. The latter was deposited first, and then the galena and sphalerite. During the major period of mineralization, the solutions contained an abundance of silica, also; and, as deposition was rapid, it was deposited as the jasperoid simultaneously with the sphalerite. When the rate of deposition had slowed down, quartz was deposited, but in relatively small amounts. The absence of silver here, as in the South-eastern Missouri district, indicates that the original magma in this metallogenetic area was free from that metal, as it was also free from gold. Ore is found adjacent to the Seneca fault of the area, which is suggestive in connection with a magmatic origin for the deposits. In a small area farther to the west, in Kansas, the Pennsylvanian sediments have been altered by hot solutions, which indicates an upward movement of hot solutions in this general region.

The prevalent view, until recent years, was that the deposits of this district were formed by meteoric waters. The inefficiency of meteoric waters to form large deposits of metals (and few are larger than those of the Tri-State area) has been repeatedly stated in this volume. A particular objection to the possibility of their having formed the ore deposits of this area is that copper is more abundant than zinc in the Mississippian limestones of the region (assuming that the determinations which have been made are correct). Copper is one of the easiest metals to transport and deposit (shown by its common occurrence in secondarily enriched minerals), yet it is not present in the ores of this area except in very small amounts. The existence, therefore, of a solution which dissolved and transported lead yet left copper behind might very well be called into question.

Production in the Tri-State Area.—From 1871 to 1917, Missouri was the leading state in the production of zinc in this area; and, because the industry centered so largely around Joplin, the area was known as the "Joplin district." As the ores decreased in quantity, prospecting led to the discovery in 1908 of the relatively high-grade ores near Miami, Oklahoma; and the development of that region followed. Missouri's production of zinc in 1917 was 132,000 tons, but the next year Oklahoma went ahead. In 1927, Missouri's production was only 18,700 tons. The extension of the mining in Oklahoma across the state line into Kansas greatly increased the production in the area, and for several years Kansas has been producing over 100,000 tons of zinc yearly. As a result of this shift of the center of production to Oklahoma and Kansas, the area was renamed the "Tri-State" district.

The production of the district in 1928 and the average tenor of the ores is shown in the following table:

TABLE 40.—THE TONNAGES OF ZINC-LEAD ORE MINED IN THE TRI-STATE DISTRICT IN 1928, AND THE AVERAGE CONTENT OF ZINC AND LEAD¹

State	Tonnage	Percent- age, zinc	Percent- age, lead	Ratio of zinc to lead
Oklahoma.....	8,028,000	2.49	0.48	5 to 1
Kansas.....	4,662,200	2.61	0.55	4.7 to 1
Missouri.....	281,300	3.22	0.41	8 to 1

¹ U. S. Bur. Mines.

A great deal of credit must go to an industry that can produce nearly 13,000,000 tons of ore that contains between \$3 and \$4 worth of metals per ton. A composite sample of 8,445 samples of ore concentrates shipped from mines near Baxter Springs, Kansas, showed an average content of 57.6 per cent zinc, 1.95 per cent lead, 2.5 per cent iron, and 0.56 per cent cadmium.

FRANKLIN, NEW JERSEY

The Franklin zinc deposits are located at Franklin (formerly called "Franklin Furnace") in Sussex County in the north end of New Jersey. Although the area is generally referred to as the "Franklin district," a similar ore deposit at Sterling Hill about 2.5 miles southwest is included. These deposits have been known for over 200 years, but the early mining was for the iron ores. According to report, zinc mining began in 1840, but how much ore was produced or what became of it is unknown. The deposit is the only one of its type in the world.

Geology of the Area.—The rocks of the area are all pre-Cambrian in age. The ores are in a coarsely crystalline marble that lies adjacent

to a gneiss, though separated from it by a fault. Pegmatite dikes cut all these rocks and the ores and have altered them all in some degree.

Mineralogy of the Ores.—The ore minerals of the deposits are *zincite*, *willemite*, and *franklinite*. Numerous other minerals are present along the pegmatite dike. More than 100 minerals, many of which are found nowhere else in the world, have been discovered in the deposits.

Mode of Occurrence of the Ores.—The ore in both the Franklin and the Sterling Hill deposits is a thin bedlike mass lying entirely within the marble. At Franklin, the flat ore body lies close to and parallel with the fault plane and dips to the southeast nearly 50° . The lower end of the ore body is folded back sharply upon the main part, giving it a hooklike form (Fig. 80). The trough of the ore body plunges to

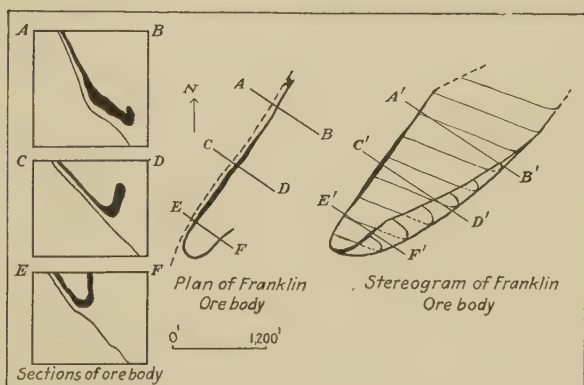


FIG. 80.—Plan, sections, and stereogram of the Franklin ore body of Franklin, New Jersey. (After Spencer, U. S. Geol. Survey Folio 161.)

the northeast. At Sterling Hill, the short hooked part of the ore body is on the underneath side; but the trough, like that at Franklin, plunges to the northeast. Zinc minerals occur disseminated through the marble but are of no economic importance.

Origin of the Ores.—Various theories have been advanced to explain the unusual zinc deposits of the Franklin district. Some men have regarded them as sedimentary deposits subsequently metamorphosed; others believe that the minerals were deposited in their present form by magmatic solutions which replaced limestones. A more likely suggestion¹ is that these minerals, though originally deposited as sulfides and other minerals by magmatic solutions, were later oxidized and then, during the metamorphism of the region, were dehydrated and decarbonated to form the present oxides and anhydrous silicates. The metamorphism caused by the intrusion of the dikes was later than the

¹ TARR, W. A., The Origin of the Zinc Deposits at Franklin and Sterling Hill, New Jersey, *Am. Mineralogist*, vol. XIV, pp. 207-219, 1929.

formation of the ores and affected them only in developing the numerous and rare minerals of the deposit.

Production.—The deposits of the Franklin district produce not only zinc but also manganese and iron, all from the three ore minerals. In 1927, the district produced over 629,000 tons of ore containing 191,390,000 pounds of recoverable zinc.

BUTTE, MONTANA

Though the Butte (Montana) district has been discussed as a copper district, its importance as a producer of zinc must be considered, at least, briefly. It has long been known that the copper ores of this area show increasing amounts of sphalerite in the outer portions of the central copper zone (see Fig. 57, p. 159), but the true zinc values were not recognized until the very rich ore of the Black Rock mine was discovered about 20 years ago. Since then, important ore bodies have been found in other mines, and Butte is now the fourth most important zinc-mining district in the United States. The ores contain considerable lead, also, no less than 24,000,000 pounds having been produced in 1928.

The geology of the area and mode of occurrence of the Butte ores have been described under Copper (pp. 159, 161). The zinc and zinc-lead ores are found in a zone which lies mainly on the north, north-west, and south sides of the central copper zone (Fig. 57). The chief minerals of the ores are *sphalerite*, *galena*, some pyrite, and varying amounts of other sulfides. The gangue minerals are quartz, rhodochrosite, and rhodonite.

The solutions that gave rise to the zinc-lead ores were of magmatic origin, but the zinc and lead minerals were deposited in the cooler areas beyond those of the more intense mineralization of the copper zone.

The Butte and Superior Company, owner of the Black Rock mine, had, in 1926, a reserve tonnage of more than 3,000,000 tons of ore averaging 14.89 per cent zinc and 5.11 ounces of silver per ton. The Emma mine, in 1926, was the largest producer of lead, the second largest producer of zinc, and the fourth largest producer of silver in the district. The Elm Orlu mine was third in the production of zinc and fifth in the production of silver and lead. Several other mines produced some lead and zinc.

ZINC DISTRICTS OF UTAH

Utah was the fifth state in the production of zinc in 1927, and as the production changed but slightly in 1928, she probably retained the same position that year. Like lead, the zinc comes from numerous mines in the Park City and Bingham Cañon districts. Very little occurs in the Tintic district. Nearly all the Utah mines that produce lead are also the leading producers of zinc. The ore has the same complex composi-

tion in all. The details of the deposits will be found under Lead and Silver (pp. 210 and 261).

ZINC AND LEAD DISTRICTS OF COLORADO

All the zinc and lead production of Colorado comes from complex ores. In *U. S. Mineral Resources* for 1927, the ore of Rico, Dolores County, is spoken of as a "lead-zinc-copper-silver-gold-iron sulfide milling ore." In 1927, Colorado ranked as the sixth state in the production of zinc in the United States and fifth in the production of lead. The districts that produced practically all the zinc and most of the lead in 1928 were (in order of their production) Leadville, Lake County; Eureka (and Silverton), San Juan County; Rico, Dolores County; and Breckenridge, Summit County.

LEADVILLE, COLORADO

The Leadville district is in Lake County, Colorado, on the western slope of the Mosquito Range near the continental divide. It is a famous

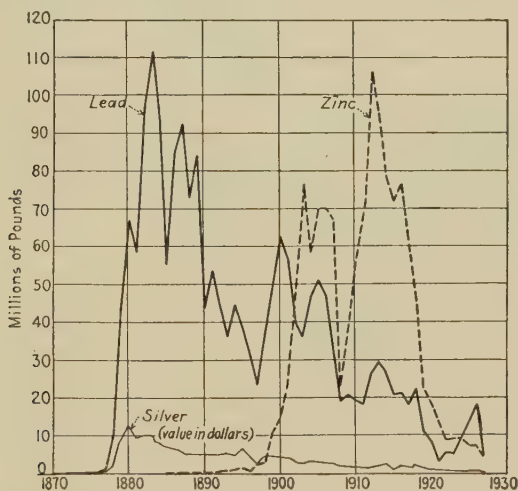


FIG. 81.—Production of lead, zinc, and silver at Leadville, Colorado. Note the tremendous increase in the production of lead following its discovery in 1875; the rise and fall of the zinc production in 10 years, and a second remarkable increase to 1912. (Data from Henderson, *U. S. Geol. Survey Prof. Paper* 138.)

one. It had its start as a gold camp called "Oro" on a gulch leading to the Arkansas River. It was worked as a gold camp for 15 years. In 1875, the silver-bearing lead carbonate ores were discovered, and the area soon became one of the world's leading lead-silver camps. During the next 4 years, the district's production of lead and silver increased enormously (see Fig. 81). Only the country of Mexico exceeded it in the production of silver during the height of its silver-mining period.

The greatest output of silver in the district was reached in 1880, and the climax in lead production came in 1883. Later there was another shift in the leading metal mined. It was discovered that during the mining of the other ores, rich oxidized zinc ores had been left untouched in parts of the old workings, and so the district became a zinc-mining camp. Manganese, gold, and bismuth are other metals produced in this remarkable locality, which covers an area of only slightly more than one square mile.

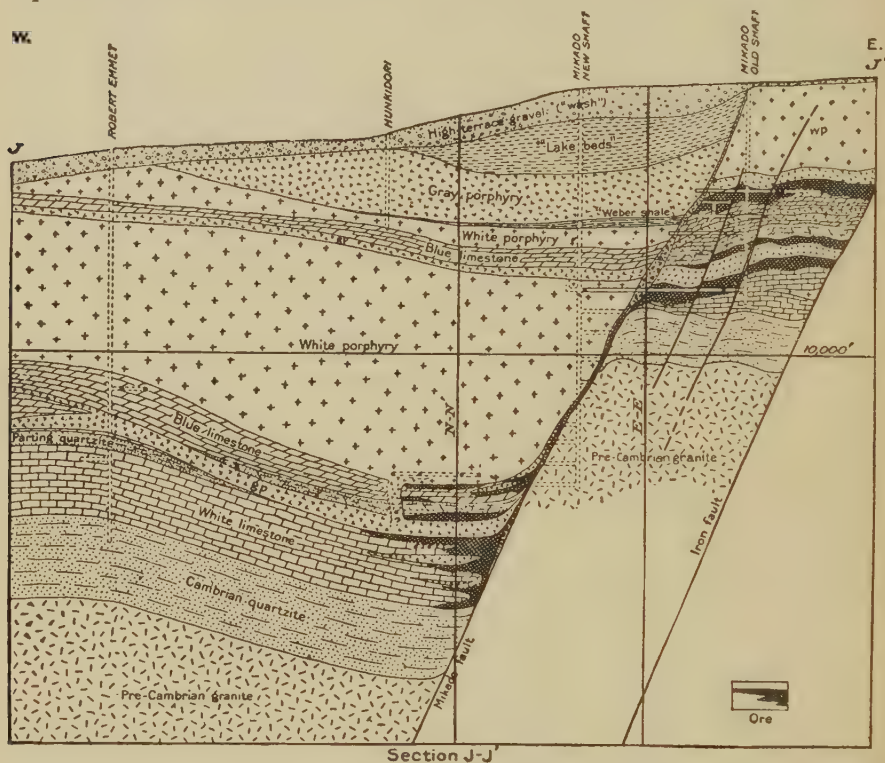


FIG. 82.—Geologic section of a part of the deposits of Leadville, Colorado, showing formations, structure, intrusive rocks, and ore bodies. (Loughlin, *U. S. Geol. Survey Prof. Paper* 148, pl. 21, 1927.)

Geology of the Area.—The formations of the district are a series of Paleozoic sediments that rest upon pre-Cambrian granite and gneiss. The ore-bearing formations are a white limestone of Silurian age, a quartzite of Devonian age, and a blue limestone of Mississippian age. These sediments have been cut by a series of intrusions now represented principally by sills, but also by dikes, of a granitic porphyry. Folding and faulting followed the intrusive period and broke up the area into blocks lying at various angles to each other (see Fig. 82).

Mineralogy of the Ores.—The *primary ore* is a fine- to medium-grained mixture of sulfides, dominantly *pyrite*, *sphalerite*, *galena*, and some *chalcopyrite*. Rarer minerals are present in some vein deposits but are not important as sources of the primary metals. The limestone near the ores contains a *manganese-bearing siderite* (Fig. 83). The gangue minerals, which are rare, are quartz, a little jasperoid, and barite.

The primary sulfides were *oxidized* near the surface into rich *silver-bearing cerussite*, *smithsonite*, and *hemimorphite*; and the primary carbonates into *iron and manganese oxides*.

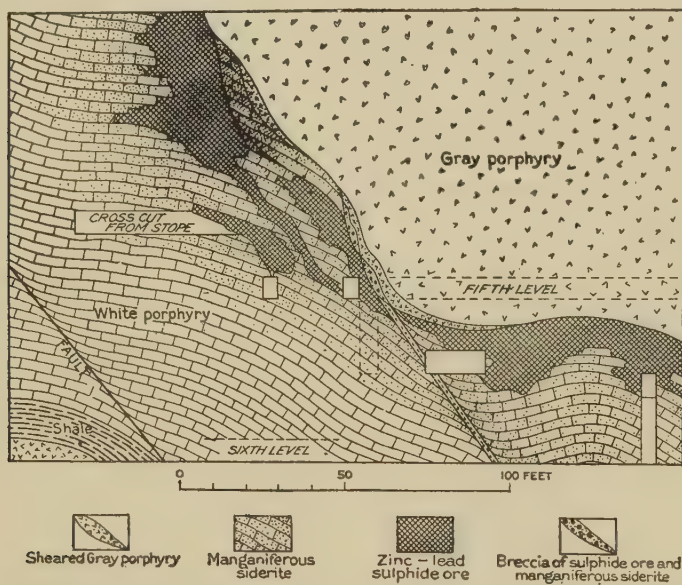


FIG. 83.—Cross section of the ore body on the fifth level of the Tucson mine, Leadville, Colorado, showing the development of manganosiderite in the limestone near the sulfide ore. (Loughlin, U. S. Geol. Survey Prof. Paper 148, Fig. 48, p. 152, 1927.)

Mode of Occurrence of the Ores.—The ores occur just beneath the porphyry and are primarily replacement deposits in the limestones. The contact of the ore with the country rock is unusually sharp for replacement deposits (Fig. 83). Some ores occur in fissures and fractured zones. Some of the veins extend downward through the Cambrian rocks into the pre-Cambrian granite. The upper parts of the deposits have been strongly oxidized, giving rise to very rich secondary ores.

Origin of the Ores.—The Leadville area was one of the very first districts of which the U. S. Geological Survey undertook to make a detailed geological study. This study was made by S. F. Emmons in 1886. Emmons regarded the ores as having been formed by descending meteoric waters, a conclusion in keeping with the general belief of the

time as to the origin of ore deposits. He continued his studies of the district for 25 years, however, and, at the time of his death, in 1911, was engaged in preparing a new report. Additional evidence secured by J. D. Irving and G. F. Loughlin (who completed the report) led to the conclusion that the primary sulfide ores were deposited by magmatic solutions. Deposition of the ores occurred after the period of intrusion that formed the porphyry sills and dikes. The ore-bearing solutions were efficient solvents but were not hot enough to accomplish much else. They rose from below and, being unable to penetrate the dense porphyries, deposited their mineral content just beneath by replacing the limestones (Fig. 83). The oxidation of the ores was, of course, subsequent and was accomplished by descending meteoric waters.

Production of the District and Tenor of the Ores.—Although at present the Leadville district is not producing so much zinc and lead as in times past, it is still an important contributor to the production of these metals. The total production of zinc and lead in the district is shown in Fig. 81, as are also the sharp fluctuations.

The oxidized ores of the district have been largely exhausted, and the complex sulfide ores furnish most of the ore at present. Of the ore mined, 62 per cent consists of zinc-lead-iron sulfides which contain 20.10 per cent zinc, 7.39 per cent lead, 0.02 per cent copper, and 4.26 ounces of silver and 0.011 ounce of gold per ton. The high-grade lead sulfide ores carry 8.94 per cent of lead and 8.50 ounces of silver and 0.143 ounce of gold per ton. These ores constitute, however, only 2 per cent of all the ores. The mines are remarkably shallow considering their large production. The majority are less than 1,000 feet in depth.

EUREKA-SILVERTON DISTRICT, COLORADO

The Eureka-Silverton district is in the central and northern part of San Juan County, Colorado. Mining began in the county in the early seventies and has continued with varying degrees of activity ever since. The use of modern flotation methods of separation has made large tonnages of complex ores available for treatment.

Geology and Deposits.—The general geology of the district is similar to that of Rico, Dolores County, and other parts of the San Juan area. The ores are vein and replacement deposits consisting largely of a complex mixture of *pyrite*, *sphalerite*, *galena*, and *chalcopyrite*. The ores also carry some *gold* and considerable *silver*. The ore from one important mine in the district, in 1925, contained 4.8 per cent lead, 7.2 per cent zinc, 0.49 per cent copper, 10 per cent iron, and 3.6 ounces of silver and 0.07 ounce of gold per ton. New ore bodies of much higher grade have recently (1927) been discovered. The Eureka deposits are unquestionably of magmatic origin.

RICO, COLORADO

The Rico district is in the southeastern corner of Dolores County, in the western part of the San Juan Mountain region. Mining began in the district in 1872, but at that time it was for silver. After the rich silver ores were exhausted, the camp became practically inactive, until more efficient methods of treating ores made it possible to develop the district's complex ores. In 1924, the value of the production there was \$24,220; in 1925, it was \$353,563; in 1926, \$990,281; in 1927, \$1,432,554; and in 1928, \$1,452,356. Zinc is now the chief metal produced, though the output of lead is nearly as large. Some silver, copper, and gold are produced, also.

Geology of the Area.—The Rico district is a part of the mineralized San Juan area. The dominant rocks are sediments ranging in age from the Devonian to the Jurassic. They dip to the west and are cut by sills and stocks of monzonite. Some faulting has occurred in the region.

Mineralogy of the Ores.—The ores of the district are the very complex ones so typical of western United States and especially of Colorado. The chief sulfides are *sphalerite*, *galena*, *pyrite*, *tetrahedrite*, and several silver-bearing minerals. Quartz and rhodochrosite are the chief gangue minerals, but calcite and fluorite are present, also.

Mode of Occurrence of the Ores.—The ores occur as *lodes* that have developed along fissures; as *blanket deposits* which parallel the bedding plane of the sediments and lie beneath impervious rocks, such as shales (Fig. 8a, p. 37) or porphyries; and as *replacement deposits* in limestones. The blanket ores are the most productive; but, because of their limited vertical range, the total volume of ore produced from them is relatively small. The veins are characterized by very fine banding.

Origin of the Ores.—The ores are evidently closely connected in origin with the igneous rocks of the area. Deposition took place near the surface.

BRECKENRIDGE, COLORADO

The Breckenridge district lies along French Creek high up on the west slope of the Rocky Mountains. It is in Summit County, Colorado, east of the town of Breckenridge. Placers were discovered there in 1860, and lode deposits in 1879. For several years, the lodes produced rich gold ores notable for the crystalline and wire gold which they contained. A fine collection of the crystalline gold from this district can be seen in the Denver City Museum. Considerable placer gold has been recovered from the streams that headed at the gold deposit. Later, the complex zinc-lead-silver ores were discovered and are now the chief ores mined.

Geology of the Area.—The sedimentary rocks of the district range from Triassic to Cretaceous in age and are cut by numerous dikes, sills,

and stocks of monzonite and monzonite porphyry. Contact metamorphism occurs where the igneous rocks cut the Cretaceous shales and limestones. Thin beds of limestone are locally altered to garnet, epidote, magnetite, and specularite; and parts of the monzonite porphyry have been converted into a mass of sericite, quartz, pyrite, and some carbonates.

Mineralogy of the Ores.—The primary ore minerals are *sphalerite*, *galena*, and pyrite, all *silver bearing*. Oxidized ores occur in the upper part of the veins. The chief gangue minerals are siderite and barite, but they are not always present in all parts of a vein.

Mode of Occurrence of the Ores.—The ores occur almost entirely as well-defined fissure veins that cut both the Cretaceous sediments and the monzonites.

Origin of the Ores.—The ores were deposited in veins by hot magmatic solutions, that spread into the wall rock beyond and altered it extensively.

SOUTHWESTERN WISCONSIN (UPPER MISSISSIPPI VALLEY) DISTRICT

The important zinc-lead district of Wisconsin is in Grant, Iowa, and Lafayette counties in the southwestern part of the state. The district extends across the state line into Jo Daviess County, Illinois. A little mining has also been done in Dubuque, Clayton, and Allamakee counties in Iowa, which are adjacent to the Wisconsin-Illinois area. This zinc-lead region is frequently spoken of as the "Upper Mississippi Valley zinc district."

The early discovery of lead in the region has already been noted (p. 196). Galena was practically the only mineral mined during the early period. It was found in the soil in many places. The climax in the production of lead was reached in 1845, after which mining slowly declined. Then followed the discovery of the deeper-lying zinc ores, and a revival in mining took place. Zinc is the chief metal produced at present.

Geology of the Area.—The only rocks found in the district are sediments. The ores occur dominantly in Ordovician rocks but, also, to a minor extent, in rocks of the Cambrian and Silurian periods. The formations given in the following list are of interest because of their connection with the ore:

	Thickness, feet
Maquoketa shale.....	160
Galena limestone.....	230
Oil rock	
Glass rock	
Platteville limestone.....	55

A bed of very fine-grained limestone at the top of the Platteville formation is known locally as the "glass rock," and a layer of bituminous shale at the base of the Galena limestone is known as the "oil rock." The beds of the district dip at a low angle to the southwest.

Mineralogy of the Ores.—The primary ore minerals are *sphalerite*, *galena*, and some *marcasite*. The gangue minerals are calcite and a little barite. The upper part of the ore bodies has been oxidized. *Smithsonite* and a little *hemimorphite* have been formed from the sphalerite; a little *cerussite* and *anglesite*, from the galena; and *limonite*, from the marcasite. The galena was only slightly altered.

Mode of Occurrence of the Ores.—The ores are in *fissures* that have been more or less enlarged by solutions, or they occur as *disseminated deposits* in the limestone near the fissures. Figure 84 illustrates the

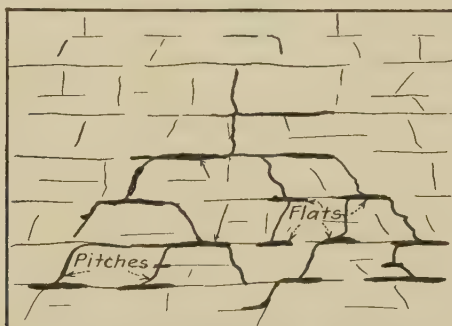


FIG. 84.—Ideal sketch of "gash" veins in the Southwestern Wisconsin zinc (lead) deposits. Note the bedded ores (flats) and the inclined veins (pitches).

character and position of the veins. Many filled fissures surround disseminated deposits, giving rise to large ore bodies (of low grade).

The sphalerite occurs almost entirely below the water level, where there is very little galena; and, as galena was abundant above, it is possible that the sphalerite has been leached out from above and deposited below.

Origin of the Ores.—The deposits of the Southwestern Wisconsin district are generally regarded as being due to concentration by meteoric waters. The ores occur dominantly above the impervious bituminous shale at the base of the Galena limestone; and, as there is no evidence of faulting in the area, it is regarded as impossible that they could have come from below. T. C. Chamberlin believed the source of the lead and zinc to have been the disseminated particles of the metals in the Galena formation and that they were concentrated by meteoric waters. Many others concur in this view. Cox advanced the theory that they were derived from the overlying Maquoketa shales and that they were carried downward as the shale was eroded. The author of this book does not believe that either the proposed source of the metals or the method of

concentration advocated is adequate and regards the origin of the deposits as a fertile field for research. Recently (1929), Emmons has advocated a magmatic origin for them.

Production of the District.—In 1927, the Southwestern Wisconsin district produced 1,480,800 tons of ore. This ore averaged 2.79 per cent zinc and 0.14 per cent lead.

ZINC-LEAD DISTRICTS OF NEW MEXICO

The production of zinc and lead in New Mexico comes from widely scattered mines. The leading producers in 1927 (in the order of their production) were the Pecos mine at the junction of Willow Creek and Pecos River in the western part of San Miguel County; the Hanover mines in northeastern Grant County; the Magdalena (Kelley) mines in central Socorro County; and the San Pedro mines in southwestern Santa Fe County (see Fig. 76, p. 206).

The Deposits.—The ores in all the districts are complex sphalerite-galena-pyrite ores. Some contain chalcopyrite and a few other minerals. The ore of the Pecos mine occurs in a sheared, micaceous diorite. At Hanover, the zinc ore is associated with a contact-metamorphic deposit occurring where a quartz diorite porphyry cuts the Carboniferous limestone. The deposit at Magdalena is in a Carboniferous limestone that has been intruded by granite porphyry. The limestone was altered by the intrusion, and large bodies of sphalerite with a little galena and chalcopyrite were deposited in it. The oxidized zone contains considerable cerussite, which is being mined at present (1928). Silver occurs with the galena. The San Pedro or New Placers district produces a lead-silver ore and a zinc ore. All of these New Mexico ores are of the complex sulfide type commonly deposited by magmatic waters.

EASTERN TENNESSEE

There is an important mineralized belt in eastern Tennessee, beginning in Jefferson County and extending northeast into Virginia. This belt contains several zinc mines one of which, the Mascot mine, made a large production in 1928. The Embree mine was also productive that year. The mines of the Bertha Mineral Company of Wythe County, Virginia, are probably in this same mineralized belt.

Geology and Deposits.—Most of the ore of the region occurs in the Knox dolomite (Cambro-Ordovician). The ores occur mainly as replacement deposits in dolomite and limestone and as a cementing material in brecciated zones that may or may not be faulted areas. Those of the Mascot mine are dominantly sphalerite with practically no galena. The sphalerite is unusually pure and is light colored. Dolomite, calcite, and very rarely barite are the chief gangue minerals. Oxidation has produced large deposits of carbonates and some hemimorphite. In

1928, better ore bodies were discovered in the deeper parts of this mine. The Embree mine produces chiefly zinc silicate and carbonates. The ores occur as residual deposits on top of the magnesian limestone of the area.

Origin of the Ores.—Though the theory of concentration by cold meteoric waters has been applied to these deposits, it is more probable that they are of magmatic origin. Especially does this seem to be true since the recent discovery of the deep-lying, rich sulfide ores. The magmatic solutions probably arose along the faulted and brecciated zones, depositing the ores in the fissures and as replacements in the limestone.

IMPORTANT FOREIGN DEPOSITS OF LEAD AND ZINC

Lead and zinc deposits are widely distributed, and every continent makes important contributions to the total world production of these metals. The location of the principal deposits is shown on the world maps, Figs. 85 and 86.

Lead and Zinc Deposits of Mexico.—Mexico's chief lead region is in southern Chihuahua, western Coahuila, Durango, and eastern Sonora. The ores are complex sulfides of lead, zinc, silver, copper, antimony, and gold. They occur as chimney-like replacement masses in limestone. The upper parts of the deposits are oxidized and have furnished much bonanza ore. There are considerable reserves of the complex sulfide ores. The Santa Eulalia mines in Chihuahua are very famous and are estimated to have produced between \$300,000,000 and \$500,000,000 worth of lead and silver. The important zinc mines of Mexico are in Coahuila.

Australian Lead and Zinc Deposits.—The Australian deposits are at Broken Hill, New South Wales; and at Mount Isa, Queensland. The Broken Hill ores are of a very high grade, averaging, in 1927, 10 to 15 per cent lead, 9 to 14 per cent zinc, and 2.5 to 5 ounces of silver per ton. They occur along a sheared zone in various metamorphosed, igneous, and sedimentary rocks. The lode is vertical or dips steeply to the west, and the ore lies along the footwall. The ore is a complex mixture of crushed and altered country rock, various silicate minerals, and sulfides. The upper portions of the ore body were oxidized. Tasmania has important complex sulfide ores of lead and zinc; and, since the building of an electrolytic zinc plant at Risdon, its production is increasing. An ore body, averaging 7 to 12 per cent lead, 9 to 14 per cent zinc, and 4 to 6 ounces of silver is being opened at Mount Isa, Queensland. It is estimated to contain several million tons of ore.

Canadian Lead and Zinc Deposits.—There are several lead and zinc deposits in Canada, but the chief one is that of the Sullivan mine in the Kootenay district in southern British Columbia. This is one of the greatest lead and zinc mines in America. The ore bodies are large and

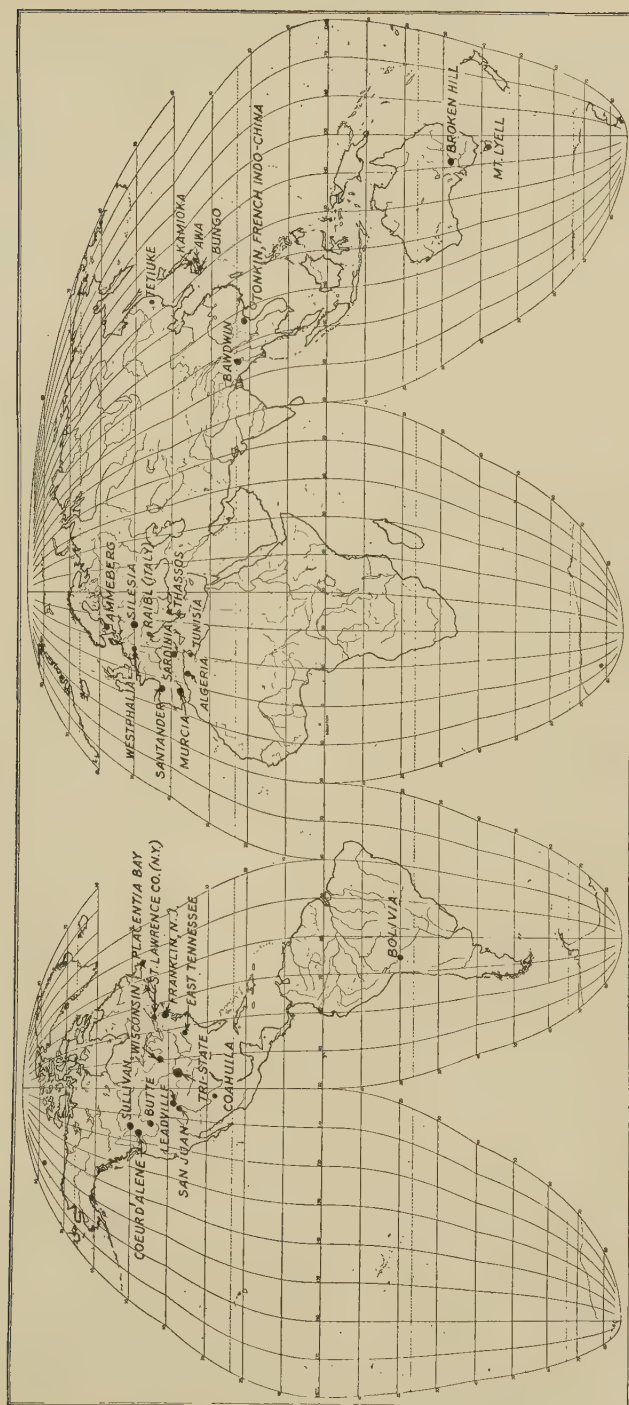


Fig. 80.—Zinc deposits of the world.

consist of galena and sphalerite, other sulfides, and some silicates. They replace a quartzite of pre-Cambrian age. A newly developed deposit in Canada is that at Bradley, Ontario, near the Sudbury nickel deposits. Zinc is produced also at Galetta, Ontario, and Tetreault, Quebec.

Lead and Zinc Deposits of Spain.—Spain has produced lead for hundreds of years, principally from the Linares and Cartagenian districts in the southeastern part of the country. The principal zinc deposits are in the provinces of Asturias and Santander along the north coast.

Zinc Deposits of Poland.—Poland now contains most of the rich zinc deposits of Upper Silesia (formerly owned by Germany). Small portions of the field are in Czechoslovakia and Germany. The Anaconda Copper Company of the United States practically controls all the deposits, except those in Germany, and is increasing the production. The Silesian deposits are the simple sulfides of zinc, lead, and iron. The ore, which replaces a dolomite of Triassic age, is high in zinc (15 to 17 per cent) and contains as much as 5 per cent lead.

Lead and Zinc Deposits of India.—The Bawdwin mines of Burma, India, are among the highest-grade lead-zinc-silver mines in the world. They are located in Tawngpeng, about 600 miles north of Rangoon. The deposits occupy a crushed, faulted zone about 400 to 500 feet wide. A number of thin lodes (some only 2 feet wide) occur in this zone. Three of them are very rich. The reserves, in 1927, were estimated at 4,100,000 tons of ore averaging 26.2 per cent lead, 16.6 per cent zinc, and 22.4 ounces of silver per ton. The ore minerals are argentiferous galena and sphalerite. There has been considerable oxidation near the surface.

Deposits of Other Countries.—Other countries that have good deposits of lead and zinc are *France, Italy, Tunisia, and Belgium.*

USES OF LEAD AND ZINC

Lead and zinc are essential metals in our modern life. They rank next to copper and iron in their usefulness. Nearly the same quantities of the two metals are used annually, although their uses are not similar except in pigments. At present, both metals are meeting with severe competition in their use as pigments.

Uses of Lead.—Lead has a long list of uses, but, as is true of all metals, certain ones greatly predominate. The most important uses of the lead consumed in the United States in 1927 are given in the following table:

TABLE 41.—PERCENTAGE OF TOTAL LEAD CONSUMED IN THE UNITED STATES, BY USES, 1927¹

Use	Percentage
Storage batteries.....	20.81
Cable coverings.....	19.15
White lead.....	14.98
Building.....	10.46
Litharge and red lead.....	4.52
Solder.....	4.16
Ammunition.....	4.04
Bearing metal.....	3.69
Foil.....	3.57
Calking.....	3.57
Castings.....	2.02
Type metal.....	1.90
Automobiles.....	1.43
Terneplate.....	0.46
Railway cars.....	0.32
Locomotives.....	0.08
Ship building.....	0.02
Miscellaneous.....	4.82

¹ U. S. Mineral Resources, 1927, Part 1, p. 342.

Use in Storage Batteries.—The use of one-fifth of the lead in storage batteries (seen from the table) indicates something as to the magnitude of the automobile and radio industries in the United States. The employment of "socket power" radio sets has considerably reduced the use of storage batteries for radio purposes, however. It is not likely that the quantity of lead used in storage batteries will greatly increase in the future, as the lead in used batteries is easily reclaimed. It is estimated that 95 per cent of the lead so used finds its way back into batteries within two or three years. It is estimated that the United States consumed 195,000 tons of new and old lead in storage batteries in 1927.

Use as Cable Coverings.—The increasing use of cable transmission lines requires nearly as much lead as is used for storage batteries. The use of underground cables is on the increase, and no less than 180,000 tons of lead was consumed for this purpose in the United States in 1927.

Use in Pigments.—The use of lead in pigments is slowly decreasing. This is true for white lead, red lead, orange mineral, and litharge. Many countries in Europe have prohibited the employment of white lead in paints because of the danger of lead poisoning to the workmen applying it. In this country, the decrease is due to the substitution of other substances, especially lithopone, zinc oxide, barium pigments, titanium oxide, and cellulose lacquers. Cellulose lacquers are extensively used on automobiles. A new lead pigment that consists of finely powdered lead

suboxide, Pb_2O , suspended in linseed oil is being put on the market. After being placed on a surface, the suboxide undergoes a slow change that leaves a thin film of metallic lead in the oil.

Use in Building.—The use of lead in building construction has been continuous from the time of the Romans. Today, this metal is used for roofing, cornices, drainage and sewerage pipes, plumbing fixtures, electrical wiring, and numerous other purposes. Brass, copper, and zinc furnish active competition in the same field, but lead is holding its place. Recently, lead mattresses have been applied between the steel frame and the foundation of skyscrapers to act as shock absorbers. About 55 tons of lead are said to have been consumed for this purpose in one building in New York.

Use in Foil.—It is of interest to note that foil may be made of (1) pure tin, (2) pure lead, (3) lead covered with tin on both sides, and (4) aluminum. When the price of tin reaches 50 cents a pound, lead foil replaces much of the tin foil.

Use in Solders.—Considerable lead and tin are used in solders. New solders that use more lead and less tin are being put on the market. One of these is made of 85 to 95 per cent lead and the remainder chiefly cadmium. Another, known as "amaloy," contains 98+ per cent lead and 1— per cent tin. Phosphorus is added to this solder to give it desired properties.

Use of Antimonial Lead.—About 4.5 per cent of the annual production of lead in the United States is antimonial lead. In 1927, 24,347 tons of antimonial lead was produced. This lead is used for type metal (see Antimony, p. 308); in storage battery grids; in cable sheathings; in hard lead for pipes, taps, and similar uses; and in solders. Antimonial lead does not meet the full demand for this type of lead, however, and much new antimony is added.

Use of Secondary Lead.—The recovery and use of secondary lead exceed those of any other metal except iron. In 1927, the recovery of secondary lead in the United States was 41 per cent of the primary domestic production. Over 276,000 tons was recovered that year. Lead is relatively insoluble, and so, aside from its use in pigments, most of its applications favor its subsequent recovery.

Uses of Zinc.—The uses of slab zinc (which is the chief smelter product) in the United States in 1927 are shown in the following table:

TABLE 42.—ESTIMATED USES OF SLAB ZINC PRODUCED IN THE UNITED STATES IN 1927¹

Use	Tons
Galvanizing:	
Sheets.....	138,500
Tubes.....	54,000
Wire.....	38,500
Wire cloth.....	6,500
Shaped materials.....	42,500
Total.....	280,000
Brass making.....	160,000
Rolled zinc.....	74,100
Other purposes ²	68,000
Grand total.....	582,100

¹ *U. S. Mineral Resources*, 1927, Part 1, p. 504, quoted from Am. Bur. Metal Statistics "Year Book."

² Includes slab zinc used for manufacture of French oxide, lithopone, atomized zinc dust, die casting, slush casting, and for the desilverization of lead.

Use in Galvanizing.—The chief use of zinc is in galvanizing. The amount used for this purpose in the United States in 1927 was 47.4 per cent of the total amount consumed.

Galvanizing is the process of coating iron with zinc. This is done to prevent the iron from rusting, the zinc being very durable. Formerly, iron was coated with zinc by galvanic action; hence the name "galvanizing." The present method, however, is to dip the sheet iron or iron object in molten zinc, first cleaning it by "pickling," which is immersing in warm dilute acid (usually sulfuric). The acid is washed off before putting the iron in the zinc bath. Melted ammonium chloride is poured over the molten zinc to prevent the zinc of the bath from oxidizing. If a high-grade, smooth product is to be made, the iron, after being cleaned in the acid, is scoured with sand. Formed objects are dipped in the bath in baskets or bundles. Any iron object, such as bolts, nuts, screws, chains, nails, wire, pipe, tubing, screens, and innumerable variously shaped forms for special purposes, can be galvanized.

Use in Brass.—Brass making has been responsible for about 30 per cent of the zinc consumption in the United States for the last 5 years. Although there is a considerable range in the amount of zinc used in brass, the amount rarely exceeds 45 per cent, and for the standard high grades of brass, it is between 30 and 37 per cent. The uses of brass are too well known to require listing here.

Use as Rolled Zinc.—Rolled zinc in sheets and strips of varying thicknesses is widely employed for special purposes. Sheet zinc is used extensively abroad for roofing but only to a minor extent in the United States.

Other Uses of Zinc.—A few thousand tons of *zinc dust* or “blue powder” are produced annually in the United States. Zinc dust contains about 90 per cent metallic zinc and about 10 per cent zinc oxide. It is used in marine (and other) paints, in dye manufacturing, and for precipitating gold from a cyanide solution. It has recently been found that zinc dust makes an excellent smoke screen.

Zinc is used in three important *pigments*: *zinc oxide*, *leaded zinc oxide*, and *lithopone*. The primary zinc content of these pigments amounted to 122,000 tons in this country in 1927. The increased production of lithopone, a barium-zinc pigment (see *Paints*, p. 525), requires a larger amount of zinc every year, but there is a decrease in the production of the other two zinc pigments.

A small quantity of zinc is used in various *chemicals* and *medicines*. Zinc is used also in numerous *alloys* with copper and other metals. The so-called “manganese bronze,” used in propeller screws, consists of 88 per cent copper; 8.7 per cent zinc; 1.5 per cent tin; and a little lead, iron, and phosphorus. “German silver” consists of 60 per cent copper, 20 per cent zinc, and 20 per cent nickel.

The *secondary recovery of zinc* is small in comparison to that of iron and lead. This is due principally to the fact that in its chief uses and forms, *i.e.*, in pigments, galvanizing, zinc dust, and zinc salts, very little of the zinc can ever be recovered. Due, also, to the volatility of zinc, there is a large loss during milling and metallurgical processes. In 1926, the amount of secondary zinc recovered in the United States was less than one-fourth of the amount produced that year from the mines.

PRODUCTION OF LEAD AND ZINC

Production of Lead and Zinc in the United States.—The production of lead and zinc in the United States comes from 24 different states and territories. Not all produce both metals, however, as of the 21 states producing lead, 5 do not produce zinc; and of the 20 producing zinc, 3 do not produce lead. The lead and zinc production of the 10 leading states in 1927 is given in the following table:

TABLE 43.—THE MINE PRODUCTION OF LEAD AND ZINC IN THE 10 LEADING STATES IN 1927¹

Lead		Zinc	
State	Tons	State	Tons
Missouri.....	198,760	Oklahoma.....	206,611
Utah.....	151,285	Kansas.....	109,427
Idaho.....	151,019	New Jersey.....	95,695
Oklahoma.....	51,680	Montana.....	80,231
Colorado.....	33,386	Utah.....	49,593
Kansas.....	27,497	Colorado.....	35,865
Montana.....	17,949	Wisconsin.....	32,841
Arizona.....	9,933	New Mexico.....	29,802
New Mexico.....	8,026	Idaho.....	26,778
Nevada.....	7,892	Missouri.....	18,737

¹ U. S. Bur. Mines, 1927.

This table represents the production from the mines, which is of far more interest from a geological standpoint than the smelter production. It shows that eight states produce both lead and zinc in important quantities; and that, of the others, two produce lead and two zinc. The large output of the first three states in each list is notable. The production figures show that the occurrence of lead is more centralized than zinc.

Missouri has contributed about 30 per cent annually of the total lead production in the United States for many years. At present (1928), approximately 99 per cent of this state's production comes from the great lead belt of the southeastern section. Years ago, a fair production of lead was made in southwestern Missouri, but at present it is insignificant. Oklahoma, the leading state in production of zinc, produces approximately 4 tons of zinc to 1 ton of lead. These figures indicate the present ratio of the zinc to lead in the Tri-State district, as the same ratio holds for Kansas, the second state in production. The shift of the main producing area in the Tri-State district from Missouri to Oklahoma and Kansas is an example of a common occurrence in mining districts. This shift began in 1915, and in 1927 Missouri produced only 4.5 per cent of the zinc mined in the Tri-State district.. Utah passed Idaho in the production of lead in 1925, but the two states are equal at present. Idaho's production is made largely from the great Cœur d'Alene district, and Utah's from numerous mines at Tintic, Park City, and Bingham Cañon. The same districts furnish Utah's zinc production. New Jersey's production comes entirely from the zinc deposits at Franklin and Sterling.

The first production of lead in the United States was made in Missouri in 1720, at Mine La Motte, Madison County. Production of zinc began in 1858 at South Bethlehem, Pennsylvania. From 1720

to 1927, a total of 19,473,786 tons of lead, and from 1858 to 1927, a total of 11,617,608 tons of zinc was produced in the United States. The annual output of lead from 1870 to 1928 is shown in Fig. 72 (p. 195). Few products show a more uniform rate of increase in production. The annual production of zinc from 1870 to 1928 is shown in Fig. 73 (p. 196).

World Production of Lead and Zinc.—The world production of lead in 1927 was 1,703,000 metric tons, and of zinc, 1,310,000 metric tons. The United States produced 37.3 per cent of the world's lead and 41.02 per cent of the world's zinc that year. The leading countries and their production of both metals in 1927 are shown in the following table:

TABLE 44.—LEADING COUNTRIES OF THE WORLD IN THE PRODUCTION OF LEAD AND ZINC, 1927¹

Lead		Zinc	
Country	Metric tons	Country	Metric tons
United States.....	635,651	United States.....	537,519
Mexico.....	227,870	Belgium.....	199,090
Australia.....	167,616	Poland.....	150,375
Spain.....	144,023	Germany.....	84,102
Canada.....	135,854	France.....	82,650
Germany.....	81,800	Canada.....	66,413
India (Burma).....	67,027	Tasmania.....	50,361
Poland.....	28,868	Great Britain.....	42,541
France.....	24,900	Netherlands.....	26,268
Italy.....	23,774	Japan.....	17,558

¹ Data U. S. Bur. Mines.

Selected Readings on Lead and Zinc

GENERAL

EMMONS, W. H.: "The Principles of Economic Geology," pp. 474-498, McGraw-Hill Book Company, Inc., New York, 1918.

PEHRSON, ELMER W.: U. S. Bur. Mines *Econ. Paper* 2, 1929. Summarizes the data on world production of zinc. Good.

RASTALL, R. H.: "The Geology of the Metalliferous Veins," pp. 281-312, Cambridge University Press, 1923.

RIES, H.: "Economic Geology," pp. 621-657, John Wiley & Sons, Inc., 1925. Contains excellent bibliography.

HYDER, F. B.: Lead and Zinc, Spurr's "Political and Commercial Geology," pp. 261-316, McGraw-Hill Book Company, Inc., New York, 1920.

U. S. Mineral Resources and *Mineral Industry* contain important material on production.

SPECIAL

Bingham Cañon: J. M. Boutwell, *Prof. Paper* 38, 1905.

Breckenridge, Colorado: F. L. Ransome, *Prof. Paper* 75, 1911.

Cœur d'Alene, Idaho: Ransome and Calkins, *Prof. Paper* 62, 1908.

Leadville, Colorado: Emmons, Irving, and Loughlin, *Prof. Paper* 148, 1929.

Park City, Utah: Boutwell and Woolsey, *Prof. Paper* 77, 1912.

Tintic, Utah: Lindgren and Loughlin, *Prof. Paper* 107, 1919.

CHAPTER VIII

GOLD AND SILVER

Gold and silver have long been regarded (and still are) as the “precious metals,” a title they hardly merit at present (1929), however, as a number of other metals are much more valuable. Platinum is worth about four times as much as gold, and a few other elements cost still more. The relative value of some of the most expensive and some of the most widely used metals today is shown in the following table:

TABLE 45.—VALUE OF SOME OF THE MOST EXPENSIVE AND WIDELY USED METALS, 1928

Metal	Value per avoirdupois pound
Iron.....	\$ 0.007
Lead.....	0.058
Zinc.....	0.061
Copper.....	0.144
Silver.....	8.530
Gold.....	301.430
Platinum.....	1,166.640
Radium.....	31,750,000.000

Throughout the ages, man has sought to become the possessor of gold and silver, and the search for them has lead him into every nook and corner on the surface of the earth. No physical difficulty has been great enough to deter him from attempting to secure gold.

Today, gold is accepted (whether wisely is to be questioned), as the standard of value¹ by most of the nations of the world. This use of the metal as a standard of value is its chief one; for, aside from that and its employment in jewelry, ornamentation, and objects of art, gold has few uses.

Early History of Gold and Silver.—The date of the discovery and first use of gold and silver by man is unknown. As shown in Chap. I of this book, it was far back in man’s early history. Although philologists believe they have proved that Ophir (the place reputed to be the source of the Queen of Sheba’s gold) was located in India, there is little geological evidence to support their view. The discovery, moreover,

¹ An ounce of gold contains 480 grains. The standard gold dollar of the United States contains 23.22 grains of pure gold. Dividing the number of grains in an ounce by the number of grains in a dollar gives 20.6718346+, or \$20.67, as the value of an ounce of gold in the United States.

in 1866 of ancient gold mines and various ruins in Zimbabwe in southern Rhodesia has apparently settled the question, for the numerous articles found in the ruins proved that the mines had been worked by the Sabæans, an Arabian people ruled by the Queen of Sheba. These mines were evidently the source of the gold given to King Solomon by the Queen. The mines of Ophir, if this Rhodesian locality was Ophir, were later worked by the Jews and the Phœnicians, under King Solomon and King Hiram, respectively, as is shown by other objects found there. A well-defined trail (along which are numerous ruins) leads from the mines to the sea, whence transportation by water to the Mediterranean region was easy.

For the most part, the deposits worked by the ancients were probably rich. Few important gold deposits occur in southwestern Asia, northern Africa, or southern Europe. The Romans secured some gold from Spain, as the Carthaginians had done before them.

Gold and Silver in the Americas.—The stories of Marco Polo about the wealth of gold in eastern Asia, undoubtedly had a part in inciting Columbus to attempt a western route to the East Indies, for his men sought for gold as soon as America was reached. Other explorers followed rapidly, and the robbing and murdering of the Aztecs in Mexico and the Incas in Peru for the gold and silver they had won from their mines is a black spot in the history of humanity. The Mexican mines were rich, and an enormous amount of silver and gold was produced from them during the centuries following the discovery of America. It has been stated that \$3,398,664,400 worth of silver was produced in Mexico between 1493 and 1895. This was more than one-third of the world's production of silver during those four centuries. Bolivia, Peru, and Chile have also been important producers. Western United States and Mexico yield over 65 per cent of the world's silver today (1928).

History of Gold and Silver Mining in the United States. *Gold Mining in Eastern United States.*—Curiously enough, although the early explorers were all seeking gold and, to a lesser extent, silver, these metals were not discovered in paying quantities within the United States until over 300 years after the discovery of the continent. Gold was found in North Carolina in 1801 (actually in 1799, but it was not known to be gold), and for 30 years much prospecting was done in the Carolinas, Virginia, and Georgia. The discovery of gold in Georgia in 1829 sent the value of the yearly production up to \$200,000. Other strikes of considerable value would cause much excitement for a while, which would then die down. The climax in production came in the early fifties, following a period of excessive swindling; and, as the California gold mines had just been discovered, the mining population headed west.

Gold Mining in California.—The greatest event in the history of gold mining in the United States began with the discovery by John Marshall,

on Jan. 19, 1848, of gold in a millrace for a sawmill he was constructing on the American River, near Coloma, California (see x, Fig. 96, p. 250). Marshall was not certain that the material he had found was gold so sent it to San Francisco by a friend to have it assayed. The friend, when he learned that it was gold, returned, bringing with him a miner from Georgia. Claims were staked out, and all went to work. The great richness of the gravels was soon discovered, and a rush for the California gold fields began. Men came from every country on the globe. Those from Mexico, Peru, and Chile arrived first, but others followed rapidly. Those from eastern United States and Europe, who went around by Cape Horn, did not begin to appear until July and August, 1849, but they soon swept aside the early arrivals. Those who traveled overland began to arrive in September, 1849. It is estimated that from July, 1849, to January, 1850, 90,000 men reached the camp and that one-fifth of them died within 6 months as a result of privations encountered on the trip or at their destination. The discovery of the very rich gold placers of Australia in 1851 did not cause an exodus of miners from California, because the extraordinarily rich California placers were not yet exhausted. Fortunes were quickly made and as quickly lost. Swindlers were especially active and reaped a harvest. In 1855, the terrace gravels buried under lavas in Toulumne County were discovered. These were enormously rich, a quart of gravel in some places containing a pound of gold (worth about \$300). In many places, \$100,000 worth of gold was recovered from 10 square feet of gravel.

Discoveries of Gold in Various Places in the West and North.—Miners traveling overland to California discovered placers of gold in various parts of the Rocky Mountains. These never gained the prominence, however, nor produced so much gold as the California placers. The great gold and silver deposit known as the "Comstock lode" was discovered at Virginia City, Nevada, by a man named Joe Kirby in 1858. Another rush ensued, followed by a period of wild speculation and swindling. During the first 8 years, between \$65,000,000 and \$70,000,000 worth of gold and silver was produced from this lode. Throughout the period of 1860 to 1880, new gold and silver camps were being discovered. Gold deposits in South Dakota, later known as the "Homestake mine," were discovered in 1876. Gold was found at Cripple Creek, Colorado, by S. W. Stratton in 1891. In 1896, the rich placers of the Klondike of northwestern Canada caused a rush of gold seekers to the frozen north. Then followed, in rapid succession, discoveries of gold at Tonopah, Nevada, in 1900; Nome, Alaska, in 1900; and Goldfield, Nevada, in 1904.

Discoveries of Silver in Western United States.—In the main, silver has been produced with gold, as at Virginia City and Tonopah, Nevada; or with lead, as at Leadville and Aspen, Colorado, and in the Cœur

D'Alene district of Idaho. The dates of the discovery of ore in several other camps producing silver are as follows: Bingham Cañon, Utah, 1863; Eureka, Nevada, 1864; Phillipsburg, Montana, 1867; and Breckenridge, Colorado, and Tintic and Park City, Utah, 1869.

Abundance of Gold and Silver.—Traces of gold and silver are found in rocks of various kinds. The estimates of Clarke and Washington give 0.000,000,X ($X = 1$ to 9) per cent gold in the earth's crust and 0.000,00X per cent silver. Berg's figures are 0.000,000,1 per cent gold and 0.000,004 per cent silver. Numerous tests have been made for these metals in rocks; and, though the amounts found vary widely, they are always small. Gold occurs in minute grains in rocks and in sands and gravels. Ordinarily, they are invisible, though particles so fine that it requires 2,000 of them to be worth one cent can be recognized by the naked eye. These recognizable grains are called "colors." Gold and silver are found in sea water but in very small quantities.

Mineralogy of Gold and Silver.—Gold does not readily enter into combination with other elements; hence, the number of gold minerals is small. Native gold is by far the most common form. Gold does form alloys, however, with silver, mercury, copper, platinum, and other metals. Silver occurs native and in combination with many elements; no less than 47 silver minerals are listed in Dana's textbook of mineralogy. Only three of them are common, however, and only four others are moderately so. Tetrahedrite, a copper-antimony sulfide, and galena are very commonly silver bearing and are important sources of silver in many mines. The common gold and silver minerals are given in the following table:

TABLE 46.—COMMON GOLD AND SILVER MINERALS

Mineral	Composition	Percentage of metal
Gold		
Native gold.....	Au	100
Calaverite.....	AuTe ₂	43
Silver		
Native silver.....	Ag	100
Argentite.....	Ag ₂ S	87.1
Cerargyrite.....	AgCl	75.3
Proustite.....	Ag ₃ AsS ₃	65.4
Pyrrargyrite.....	Ag ₃ SbS ₃	59.9

Physical Properties of Gold and Silver Minerals. *Native Gold.*—Gold rarely occurs as crystals; those that do occur are generally octahe-

drons (note surface of sheet gold in Fig. 87). More commonly, gold is massive in the form of grains, nuggets, sheets (Fig. 87), and wires. The color is gold-yellow, becoming a lighter yellow if silver is present. The luster of gold is metallic. Its hardness is 2.5 to 3, and its specific gravity is 15.6 to 19.3 (19.33 if pure). Gold has no cleavage and is very malleable and ductile. It is insoluble in common acids. Native gold is the most common gold mineral. It is usually included in other minerals and is especially common in quartz and, to a lesser extent, in pyrite.



FIG. 87.—Native gold from Farncomb Hill, Breckenridge, Colorado, showing the characteristic structure of intersecting thin plates covered with the triangular crystal faces of the octahedron. Photograph by Schwartz from a specimen in the Campion collection, Colorado Museum of Natural History, Denver. (*Ransome, U. S. Geol. Survey Prof. Paper 75, pl. 19.*)

Calaverite.—There are two gold tellurides, but calaverite is the more important as a source of gold, and it is restricted to a few districts. It occurs as crystals, which are usually long and thin; but it is also granular. The color of calaverite is silver-white. Its hardness is 2.5, and its specific gravity is 9. It is the important ore mineral at Cripple Creek, Colorado, and Kalgoorlie, West Australia.

Native Silver.—Silver occurs in crystals, as wire silver, massive sheets, grains, and nodules. Its color is silver-white, but it tarnishes readily to black. Its hardness is 2.5 to 3, and its specific gravity is 10.5, if pure, and higher if gold is present. Silver has a metallic luster and is ductile and malleable. Native silver is found in many districts.

Argentite.—Argentite is fairly common as octahedral crystals, commonly arranged in reticulated or arborescent forms. It occurs massive and as grains in other minerals, especially galena. Argentite is blackish lead-gray, and its streak is shiny lead-gray. It has a hardness of 2 to 2.5 and a specific gravity of 7.20 to 7.36. Argentite has a metallic luster and is perfectly sectile. It is the most common source of silver and is undoubtedly the form in which the silver occurs in galena.

Cerargyrite or Horn Silver.—Cerargyrite is usually massive, but it may occur as cubic crystals. It is normally a pearl-gray color which alters on exposure. The hardness of cerargyrite is 1 to 1.5. It is so soft that it can be indented with the finger nail. Its specific gravity is 5.55. The mineral has a resinous luster and strongly resembles wax. It is highly sectile. Cerargyrite is an important silver ore mineral, especially in the upper part of silver veins occurring in arid or semiarid regions.

Proustite and Pyrargyrite.—Proustite and pyrargyrite commonly occur in the same deposit; the former is known as "light-ruby silver ore," the latter as "dark-ruby silver ore." Crystal forms, some of exceptional beauty, are common; but both minerals occur massive as well. Proustite is scarlet-vermilion, and pyrargyrite is black to grayish-black but is a deep red by transmitted light. Proustite has a hardness of 2 to 2.5 and a specific gravity of 5.57 to 5.64; pyrargyrite has a hardness of 2.5 and a specific gravity of 5.77 to 5.86. Both minerals have an adamantine luster. Both have fair cleavage, a conchoidal fracture, and are brittle. They are of fairly widespread occurrence but are minor sources of silver.

Composition of Gold and Silver Deposits.—Gold and silver, like lead and zinc, are commonly found in the same deposit (hence their treatment, also, in one chapter). They are not associated universally, however, for there are very important deposits of each metal that are essentially free from the other.

Silver commonly occurs with lead, also, as has been seen in the discussion of the numerous lead-silver districts in the United States, and as will be seen further in the discussion in this chapter of the districts producing both silver (the dominant metal) and lead.

Gold and silver are also recovered from copper ores. The fifth most important gold-producing mining company in the United States in 1927 was the Utah Copper Company, which recovered the gold from copper and lead-zinc ores; and the company that was first in the production of silver was the Anaconda Copper Mining Company, which also recovered the silver from copper and lead-zinc ores.

The domestic supply of gold in the United States comes chiefly from dry or siliceous ore (often called "lode deposits") and placers. In 1927, these two sources yielded 76.6 per cent of the gold; in 1915, they had furnished 90 per cent.

The sources of the silver in the United States in 1927 were as follows: lead-ore, 26.44 per cent; copper ore, 24.41 per cent; lead-zinc ore, 22.85 per cent; and dry or siliceous silver and silver-gold ores, 19.75 per cent. In 1915, the production of silver from copper and lead-silver ores was nearly the same; but, between 1915 and 1927, there was a 15-per cent loss in the production from siliceous ores and a corresponding gain from lead-zinc ores.

Gangue Minerals in Gold and Silver Deposits.—Quartz is the most common gangue mineral for gold, and it is fairly common for silver. Pyrite, as well as pyrrhotite and arsenopyrite, is also a common gangue mineral for gold. Certain carbonates, sulfates, and oxides occur quite commonly with silver. As both gold and silver, however, are found with complex ores, their gangue minerals are so variable that it is impossible to give a detailed list here.

Tenor of Gold and Silver Ores.—The value of gold and silver ores is variable. A *gold ore* containing 0.1 troy ounce (worth \$1) of gold can be worked but only under favorable conditions. In 1927, the tenor of siliceous gold-silver ores in the United States ranged from \$0.69 in Alaska to \$21.45 in Idaho; the average for all siliceous ores for the year was \$3.59. Placer deposits containing as low as \$0.04 to \$0.05 worth of gold per cubic yard of gravel have been worked profitably. In 1927, the dredges working on gravels in California handled 51,300,000 cubic yards of gravel that averaged \$0.1066 per cubic yard. *Silver ores* must be richer than gold ores. Siliceous ores should contain about 15 ounces of silver per ton. The lead and lead-zinc ores may carry as low as 1 or 2 ounces of silver. The more complex ores are difficult to estimate. If they contain copper, even small quantities of silver can be recovered. The average gold-silver content of various types of ores in 1927 is given in the following table:

TABLE 47.—GOLD AND SILVER VALUES IN VARIOUS CLASSES OF ORES IN THE UNITED STATES, 1927¹

Class of ore	Amount in tons	Average value per ton
Dry or siliceous ores. . . .	8,549,720	\$3.59
Copper ore.	49,966,438	0.32
Lead ore.	2,004,729	4.89
Zinc ore.	452,490	2.18
Copper-lead and copper-lead-zinc ores.	418,601	3.07
Lead-zinc ore.	3,134,942	2.99
Total.	64,526,920	

¹ U. S. Bur. Mines.

Impurities in Gold and Silver.—Alloys of gold and silver are of common occurrence, and small quantities of various metals occur as impurities in both gold and silver. The purity of *gold* is commonly called its “fineness,” by which is meant the number of parts of pure gold in 1,000 parts. Rarely, some vein gold contains 997 to 999 parts of gold; others, as electrum (an alloy of gold and silver), contain as low as 500 parts. The fineness of most gold averages between 800 and 850. Placer gold is purer than the average and may be 950 fine, or even higher. Silver, copper, iron, platinum, bismuth, and mercury all occur in gold. Traces of other elements are found in it, also. The impurities of *silver* are even more variable than those of gold. It contains traces of all the elements just mentioned as impurities in gold, and also many others.

Treatment of the Ores.—Though the extraction of gold and silver ores from the ground involves methods that are essentially the same as

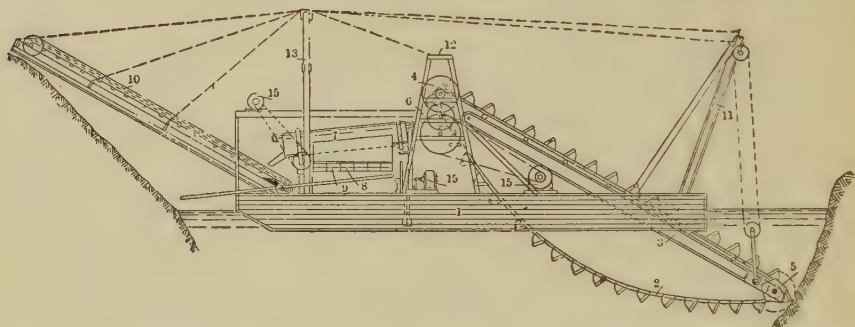


FIG. 88.—Essential parts of an open-connected bucket dredge. 1 = hull, 2 = chain-bucket line for excavating gravels at (5), 6 = hopper to receive gravels from buckets, 7 = screen to remove the coarse gravel, the gold-bearing gravels passing through on table (8) covered with riffles (9) to recover the gold, 10 = stacker to pile up coarse gravels. Fine gravels are dumped overboard. (*Eng. and Min. Jour.*, May 30, 1908, p. 1,085.)

those for the metals already discussed, the metallurgical treatment of these ores is considerably different.

Mining. Inasmuch as over 55 per cent of the gold and silver in the United States comes from siliceous ores, underground mining methods prevail. As most of these deposits are veins or lodes, the stopes are largely tabular openings following them. In the complex ores, especially in the large ore bodies, the stoping is by square sets or caving methods. A few buried placers are worked by underground methods.

Placers are largely worked by dredges at present (1929), although hydraulic methods were formerly used. A dredge (Fig. 88) is a boat upon which are built the mechanical devices necessary to dig up the gravels (usually chain buckets) and wash them to recover the gold. As the gravels in front are removed, the washed gravels accumulate behind the dredge (Fig. 89). The hydraulic method consisted of driving

a stream of water against the gravels (Fig. 90). This washed the gravels into a sluiceway (Fig. 91) on the bottom of which were numerous cross



FIG. 89.—Gravels piled up behind a dredge at Breckenridge, Colorado. (*Photograph by W. A. Tarr.*)

pieces ("riffles") which caught the gold. A little mercury introduced at the upper end of the sluiceway aided in retaining the very fine gold.



FIG. 90.—Hydraulic mining gold-bearing gravels at Atlantic City, Wyoming, in 1912. (*Photograph by W. A. Tarr.*)

Of the 1927 gold production in the United States, 21 per cent was from placers.

During prospecting and in working small deposits, panning and sluicing methods are used. The panning of gold (Fig. 92) is very easy; and, as even a few colors can be detected by this means, it was the favorite method used by the old prospector in locating a placer deposit.



FIG. 91.—Sluiceway for catching the gold. Note the hydraulic giant in action in the background. Atlantic City, Wyoming. (Photograph by W. A. Tarr.)

Extracting Gold and Silver from the Ores.—The method of extracting gold from its ores is different from the method of removing silver, unless the two metals occur together. For this reason, the two methods will be discussed separately.



FIG. 92.—Panning gold at Atlantic City, Wyoming. (Photograph by W. A. Tarr.)

If the *gold* occurs as native gold, or free-milling ore, a common method of extraction is to crush it in stamp mills until the particles are small enough to be washed through a fine screen, from which they flow over a plate coated with mercury. The gold unites, or amalgamates, with the mercury, and the waste rock passes on. This waste rock may also be treated to recover the small amount of gold it contains. From time to time, the amalgam of gold and mercury is scraped

off the plate, the two metals are separated, and the mercury is used again. Nearly 31 per cent of the 1927 gold production in the United States was recovered by the amalgamation method.

Some ores are of a grade so low or are so complex, that they are treated by different methods. Two methods can be used: the cyanidation and the smelting.

Cyanidation methods are especially suited for the treatment of low-grade ores. If necessary, as in the case of the Cripple Creek ores, the ore is first roasted to drive off the tellurium or sulfur. It is then crushed very fine and treated with a cyanide solution that dissolves the gold. The latter is precipitated by passing the solution through zinc shavings or dust, and the metallic gold is then melted and cast into bars. *Smelting* is employed for complex ores; the gold (and silver) follows the copper and lead and is recovered from them during their refining. Gold and silver are finally separated or parted by electrolytic methods. Approximately 30 per cent of the 1927 gold production in the United States was obtained from the smelting of other ores.

Silver is more difficult to extract from its ores than gold. For the purpose, several methods have been developed, which cannot, of course, be given in detail here. One, known as the *dry process*, involves the formation of an alloy with lead. The ore, which must contain both lead and silver, is roasted and melted in a furnace. The silver-lead alloy obtained may be rich enough to refine, or it may be necessary to add more silver ore to it. A common method of separating the silver from the lead is to allow the molten material to cool slowly, whereupon the lead forms crystals poor in silver. Most of the silver, therefore, remains in the liquid portion, which is then separated from the crystals. A repetition of the process gives a still richer silver-bearing liquid. Instead of this cooling method, zinc may be added to the molten silver and lead, whereupon the zinc unites with the silver and some lead and floats on the top of the molten lead. This alloy is removed by skimming, and later the zinc is distilled off, leaving an alloy of lead and silver. The final separation of the lead from the silver consists in oxidizing the lead, which then floats on the liquid and can be skimmed off. This process is repeated many times, until finally only the silver remains.

Two *wet methods* are used in extracting silver. One is known as the *amalgamation process*, in which the silver (from silver chloride) amalgamates with mercury and is then recovered by distilling off the mercury, as is done in the separation of gold. There are numerous variations of this process, for other reagents may be added to assist in the recovery of the silver. The other wet process consists in taking the silver into solution as the chloride or sulfate and then precipitating it by various means but usually as the sulfide, which is then treated to reduce it to metallic silver.

Where gold and silver occur together, the silver can be dissolved out, leaving the metallic gold behind. The former is then recovered by precipitation and further treatment to produce the metal.

MODE OF OCCURRENCE OF GOLD AND SILVER ORES

Primary Deposits of Gold and Silver.—Gold occurs chiefly in quartz veins or lode deposits and as placers; rarely it is in other forms of ore

deposits. It is a persistent mineral and, as a result, is found in deep-seated, intermediate, and shallow veins. Silver is largely confined to the shallow and intermediate veins. It occurs with lead in veins and replacement deposits and with copper in various types of deposits. Some lead-silver-zinc ores occur as contact-metamorphic deposits; but they are not at the immediate contact, for both silver and lead are deposited at temperatures lower than those prevailing at the contact. More or less gold may occur in these complex ores, but such deposits do not represent the chief mode of occurrence of gold.

Placer Deposits of Gold.—No less than 21.41 per cent of the gold produced in the United States in 1927 came from placers, and it is probable that the relative amount so produced in other parts of the world is similar. The high specific gravity, insolubility, and toughness of gold are the factors that control its formation of placers.

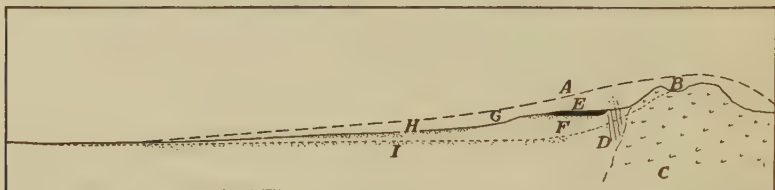


FIG. 93.—Ideal sketch showing the development of the various kinds of placers in California. A, hypothetical land surface about the beginning of the Cretaceous. B, Sierra Nevada Mountains. C, granite. D, gold-quartz veins. E, lava flows. F, buried gold placers. G, present upland surface. H, terrace placers. I, gold placers along present streams.

The weathering of the exposed portions of a vein or lode containing gold liberates the gold, which gradually finds its way into nearby stream channels. In the channel, it is mixed with other heavy minerals and is constantly shifted to lower and lower levels. It accumulates along the flat reaches of the streams and works its way to the bottom of the gravels. These gravels may be 10, 20, 50, or even more than 100 feet deep.

The particles of gold in placers range in size from mere colors, worth 0.002 cent, to nuggets that weigh over 200 pounds. A mass of gold that weighed 2,440 troy ounces and was valued at \$45,000 was found near the outcrop of a vein at Carson Hill, California, in 1854. The "Welcome Stranger" nugget, found at Dunolly, Victoria, Australia, in 1869, weighed 2,268 ounces. Although we have heard much about the Klondike and its placers, the largest nugget found there weighed 85 ounces and was worth about \$1,750. For the most part, the gold in placers consists of very fine material (gold dust). The farther the particles have traveled the smaller they are and the more rounded.

Gold is found in many black sands, which is to be expected, as the black minerals are magnetite and ilmenite and both are heavy, although not so heavy as gold. Other minerals commonly associated with gold

in placers are garnets, zircon, and less commonly platinum and the metals related to it.

If the gold is not removed mechanically, it may accumulate over the vein and develop very rich placers, as some of those in Australia. Placers have also been formed along the seashore, either on a present beach or along former beaches now raised above sea level.

Since streams have been concentrating materials throughout geologic time, it is not surprising that some gold placers have become buried in ancient rocks and are now mined. Many men believe that the world's greatest gold deposits, those of the Rand district in Transvaal, South Africa, are such buried placer deposits. The buried placers of the Sierra Nevada Mountains were very rich (Fig. 93).

Secondary Enrichment of Gold and Silver.—Gold is so difficultly soluble that it is rarely carried downward by meteoric solutions. Where manganese is present in the ore body, however, and the solutions contain chlorides, the gold may possibly be dissolved. In the main, however, it tends to concentrate at or near the surface.

Silver is more readily transported by meteoric waters than gold, but just how extensive the sulfide enrichment of silver deposits may be is not fully known. Native silver and the insoluble silver chloride cerargyrite are common in the oxidized portions of silver veins. The sulfide ores contain argentite and varying amounts of antimony-arsenic-silver minerals. These complex ores may be secondary in origin, but in some deposits they are undoubtedly primary.

PRINCIPAL GOLD AND SILVER DISTRICTS OF THE UNITED STATES

The various districts in the United States that produce gold and silver will be described under the head of their dominant mineral as gold, silver, and gold-silver districts. So many districts produce silver and lead that a separate division could logically be devoted to them. The arrangement here, however, will be to place a district in which silver surpasses lead in the chapter on gold and silver and one in which lead surpasses silver in the chapter which deals with lead. The gold and silver districts will be discussed approximately in the order of their importance.

GOLD DISTRICTS

The most important districts in the United States producing dominantly gold are Black Hills district, South Dakota; Mother Lode, Grass Valley, and the placer districts, California; Cripple Creek, Colorado; Juneau and Nome, Alaska; and Jarbridge and Goldfield, Nevada.

BLACK HILLS (HOMESTAKE MINE), SOUTH DAKOTA

The principal gold deposits of the Black Hills district are those of the very famous Homestake mine. This is located at Lead, Lawrence

County, South Dakota, in the northern part of the Black Hills. The Homestake mine has been producing gold since the discovery of the deposit in 1876. It has literally "paid from the grass roots down," as the discoverers took out about \$5,000 worth of gold from their discovery shaft. In 1877, the mine sold for \$70,000. The Homestake mine is now one of the richest of gold mines, and at one time it was the leading mine in gold production in the world.

Geology of the District.—The geology of the district is very complex. The rocks immediately associated with the ores are pre-Cambrian metamorphic rocks. They consist of schists, slates, quartzites, and marbles all of which have been intensely folded. Patches of Cambrian sediments (conglomerates, quartzites, shales, and some dolomite) rest upon the

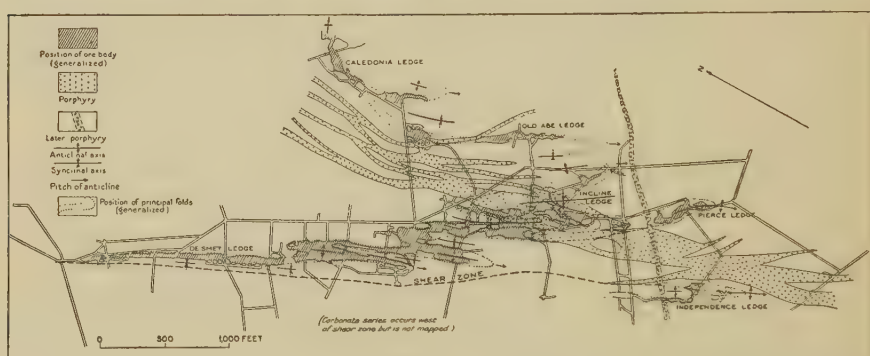


FIG. 94.—Map of the 300-foot level of the Homestake Mine, Lead, South Dakota. Note the folding of the ore body and its variations in thickness. (Map by Paige, Wright, and Hosted, U. S. Geol. Survey Bull. 765, pl. 8, p. 30.)

eroded pre-Cambrian surface. Both the Cambrian and the pre-Cambrian rocks are cut by felsitic dikes. This intrusion is generally believed to have taken place in early Tertiary times.

Mineralogy of the Ores.—The primary ore mineral is *native gold* which contains a very little silver. The gold is usually associated with arsenopyrite but also with pyrrhotite, pyrite, and other minerals. The chief gangue minerals, in addition to the sulfides just mentioned, are quartz, dolomite, calcite, and the numerous minerals found in the schists.

Mode of Occurrence of the Ores.—The ores, which are replacement deposits, occur as lenticular masses conforming to the schistosity of the enclosing rocks. The most important ore body has replaced a dolomite in the pre-Cambrian series. In some places, this ore body is the thickness of the original bed, *i.e.*, 40 to 60 feet. The beds have been greatly thickened or thinned by the crumpling that has taken place (Fig. 94). Less important deposits occur as quartz veins, siliceous ores in the Cambrian beds, and buried placers in the conglomerate at the base of the Cambrian beds.

Origin of the Ores.—The ores of the Homestake mine originated through the replacement of some of the pre-Cambrian carbonates by the gold-bearing solutions. To a lesser extent, the schists were replaced, also. Some men have sought to show that the deposits were formed in Tertiary times, but Connolly believes that they are pre-Cambrian in age. The gold placers at the base of the Cambrian beds undoubtedly had their source in the Homestake lode, which was exposed to erosion in pre-Cambrian times.

Production and Tenor of Ore.—Up to December, 1928, the Homestake mine had produced a total of \$218,654,000 worth of gold. In 1927, the ore contained \$4.87 worth of gold per ton.

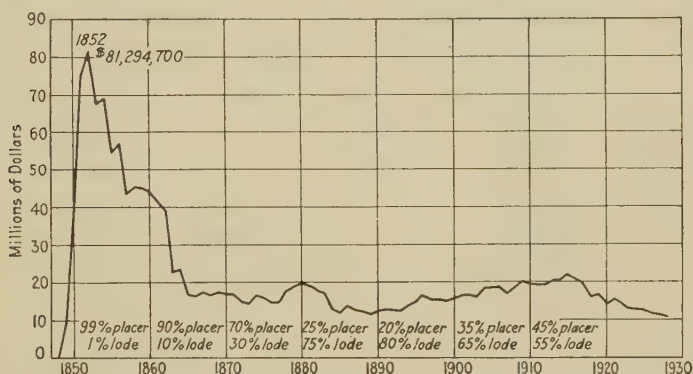


FIG. 95.—The gold production of California for 80 years, 1848 to 1928. Note the tremendous increase following the discovery of the placer deposits, reaching the peak within 4 years. (Data from *U. S. Bur. Mines Econ. Paper 3*, pp. 9-10.)

CALIFORNIA GOLD DISTRICTS

California has long been known as the “golden state,” primarily because of its great gold production. The gold comes from three districts: (1) the Mother Lode belt, (2) the Grass Valley district, and (3) the district of the placer deposits. These districts are on the western slope of the Sierra Nevada Mountains. The Mother Lode belt lies south of the Grass Valley district, and the placers are west of both. No less than 8 of the 25 leading gold-producing companies of the United States are located in these 3 districts. The total production of gold from these California districts from 1848 to 1928 amounted to 6,049,129 pounds (avoirdupois), worth \$1,823,556,360 (see Fig. 95).

MOTHER LODE BELT

The Mother Lode belt is a zone about 1 mile wide and 120 miles long. It begins near Georgetown, Eldorado County, California, and extends southeast along the western slope of the Sierra Nevada Mountains to Mariposa, Mariposa County. It lies in 5 counties: Eldorado, Amador,

Calaveras, Tuolumne, and Mariposa (see Fig. 96). The Mother Lode belt is one of the famous gold-mining districts of the world. The gold-quartz veins were discovered in August, 1849, a year and a half after the finding of the placer gold on American River. They were discovered in Mariposa County near the south end of the Mother Lode district, and the placer gold had been found in Eldorado County near the north end. Since then, gold has been produced at many points along the belt, for although the quartz veins are practically continuous throughout its length, they do not carry everywhere sufficient gold to mine.



FIG. 96.—Map showing the location of the Mother Lode Belt; Nevada City-Grass Valley district; and the location of the place (marked x) where gold was discovered in 1848. (Modified after Knopf, *U. S. Geol. Survey Prof. Paper* 157, Fig. 1, p. 2.)

Geology of the District.—The country rocks of the Mother Lode belt are slates, schists, greenstones, and serpentinite. The rocks strike north-west and dip steeply to the east (Fig. 97). The dip averages about 70° . The original rocks were Carboniferous sediments (shales) interbedded with tuffs and lavas. These rocks were metamorphosed at the end of the Paleozoic era and later were subjected to intrusions now represented by various dioritic, granitic, and other rocks. During the metamorphism, the tuffs and lavas became the greenstones, and the shales became the slates.

Mineralogy of the Ores.—The only ore mineral of importance in both the quartz veins and the mineralized country rock is *native gold*. Aside from quartz, pyrite is the most common gangue mineral in the veins; but some arsenopyrite, sphalerite, galena, and chalcopyrite are found. The ore in the country rock contains ankerite (a calcium-magnesium-iron

carbonate) and the minerals found in the schists and greenstone. The minerals of the deposits are dominantly gold and quartz.

Mode of Occurrence of Ores.—The gold ores occur as gold-quartz veins (Fig. 97) and as "mineralized country rock." The veins are well defined and show little variation from one end of the district to the other. They usually occur as several parallel veins. Knopf states that as many as four of these may be worked in one mine. A single quartz vein is rarely more than a few thousand feet long. The veins do not conform to the structure of the slates and other rocks but follow fault planes that cross the cleavage planes of the slates at an acute angle (Fig. 97). They vary much in thickness. The ore is usually in shoots (of considerable vertical length); therefore, the gold values are very irregularly distributed along the belt or district. The ore of the mineralized country rock is of two types: a gray ore resulting from the introduction of the minerals into the greenstones adjacent to the veins, and a schist ore that is the result of the alteration of certain hornblende and chlorite schists.

Origin of the Deposits.—The solutions that deposited the quartz veins and formed the ores in the country rock came from a deep-seated magma. Knopf holds that most of the quartz was formed by the alteration of the vein walls. Many of the veins have been re-opened and additional quartz deposited. The deposits were formed in late Jurassic or early Cretaceous times.

Production and Tenor of the Ores.—From 1849 to 1928, the great Mother Lode district produced over \$251,000,000 in gold. It was the erosion, moreover, of the upper part of the gold-quartz veins of the district that contributed a considerable amount, if not most, of the gold formed in the placers, especially those of Eldorado County. At present (1928), the major production of the Mother Lode district comes from Amador County. Almost all the deep mines (some have vertical depths

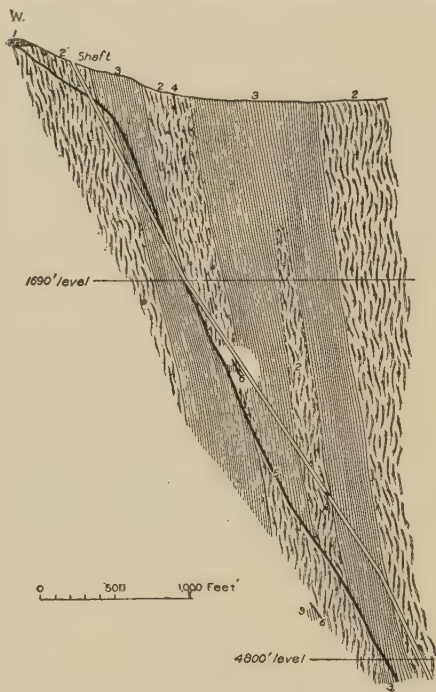


FIG. 97.—Section through the Argonaut shaft, Mother Lode district, California, showing the vein crossing the steeply dipping slates. 1, Tertiary gravel; 2, greenstone; 3, black slate; 4, augite melaphyre (flow or sill); 5, Argonaut vein; 6, gouge veins. (Knopf, *U. S. Geol. Survey Prof. Paper* 157, Fig. 18, p. 67.)

of 4,500 feet) are in this county, which has produced nearly half of the total output of the district. The gold-quartz ore of the veins is of moderate grade, averaging about \$7.50 per ton. Formerly, ore as low as \$2 or \$3 per ton was mined, but this is impossible today. The gray ore of the mineralized country rock averages \$8 per ton and is an important source of gold in several mines. The schist ore of this rock is usually of a low grade, only \$2 or \$3 per ton.

GRASS VALLEY-NEVADA CITY DISTRICT, CALIFORNIA

The Grass Valley-Nevada City district is in Nevada County, California. It lies north of the Mother Lode belt (see Fig. 96). Placer County, which contains a number of smaller unrelated gold mines, lies between the two districts. This northern district contributes an important part of California's gold production.

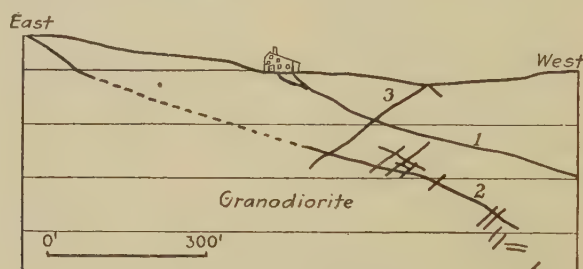


FIG. 98.—Section along the Pennsylvania vein (1) in granodiorite, Grass Valley, Nevada County, California. 2, W. Y. O. D. vein. 3, Crescent vein. Looking south along the strike of the vein. Note the low dips of the veins. (After Lindgren, *U. S. Geol. Survey 17th, Ann. Rept.*, Part 2, p. 248, 1896.)

Geology of the District.—The country rock of the district is dominantly a granodiorite, which is the result of an intrusion into metamorphosed sediments of late Paleozoic age. The intrusion occurred during the early Cretaceous period.

Mineralogy of the Ores.—The gold occurs as *native gold* in massive quartz. A few other minerals are present, chiefly pyrite, chalcopyrite, sphalerite, galena, and arsenopyrite. All of these sulfides are gold bearing in some degree.

Mode of Occurrence of the Deposits.—The gold deposits are strong, well-defined quartz veins, that occur dominantly in the granodiorite (Fig. 98) but also in the Carboniferous sediments and in a diabase. There are two important vein systems; one set strikes north and south and dips either east or west, and the other strikes east and west and dips either north or south. For the most part, the dip is flat, but it varies widely. The veins are from a fraction of an inch to 15 feet or more thick.

Origin of the Ores.—There appears to be little doubt but that the gold-quartz veins were formed by hot solutions given off from some deep-

seated magma, although the evidence for this is not entirely clear. The solutions were able to produce marked changes in the wall rocks along the veins.

THE PLACER DEPOSITS

Few placer deposits have been discovered that were as rich as the California ones. These are found along the west slope of the Sierra Nevada Mountains from Mariposa County to Plumas and Butte counties. The gravels along the rivers that drain to the southwest from the Sierra Nevada Mountains contain gold in varying amounts. Those of the American and Yuba rivers contain the largest amounts of gold, but the gravels of the Feather, Bear, and other rivers contain considerable amounts, also. California placers produced, between 1848 and 1928, no less than \$1,226,915,404 worth of gold.

Mode of Occurrence and Origin of the Placers.—The gold-bearing gravels of this district occur in the channels, flood plains, and terraces of present rivers and as buried placers high above the rivers.

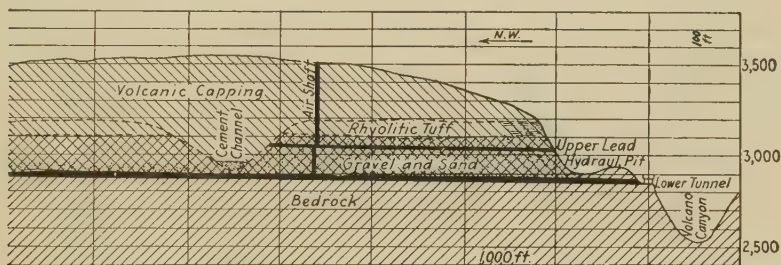


FIG. 99.—Placer gravels buried under volcanic rocks, Forest Hill Divide, Placer County, California. Note tunnel used to mine the gravels and the hydraulic pit at the right. (After Browne and Lindgren, *U. S. Geol. Survey Prof. Paper 73*, pl. 25.)

During late Jurassic or early Cretaceous times, intrusions of granitic masses occurred that formed the Sierra Nevada Mountains. Following these intrusions, the gold-quartz veins were formed in the adjacent metamorphic rocks. Rapid erosion then took place in this newly uplifted area, and as the streams cut down the mountains, the veins were exposed (Fig. 93, p. 246) to weathering which broke up the quartz and freed the gold. The wearing down of the land surface and concentration of the gold in stream-made deposits continued throughout the late Cretaceous period and nearly to the end of the Tertiary. The gold that was originally distributed through hundreds and probably thousands of feet of veins was concentrated in these gravels.

Near the end of the Tertiary period, violent volcanic action broke out in the northern part of this area, and lavas filled the valleys and spread far and wide over the region. After the volcanic action had

ceased, the streams soon cut through the lavas and developed sharp valleys, that were gradually deepened as the Sierra Nevada Mountains were again uplifted. The new streams cut into the gold-bearing gravels of the early period, and the process of concentrating was again underway. The finer gold particles were swept far out into Sacramento Valley, and the coarser were concentrated along the upper reaches of the streams. The placers buried by the lavas are now found at various elevations along the sides of the valleys (see Fig. 99) cut since the eruptions. These placers were discovered in 1852 and have contributed a large quantity of gold to the total placer production.

Gold Values of the Gravels.—The gold is not uniformly distributed through the gravels but occurs as “pay streaks” and decreases in value outward from these richer portions. The buried placers cannot be worked where they fall below \$1 per cubic yard in value, but the modern dredge can profitably work surface gravels containing as low as \$0.05 or \$0.06 cent worth of gold per cubic yard. The gold is comparatively fine, large nuggets being rarely found near the original vein.

CRIPPLE CREEK, COLORADO

The Cripple Creek district is located in Teller County, Colorado. It lies on the west side of Pikes Peak at an elevation of about 10,000

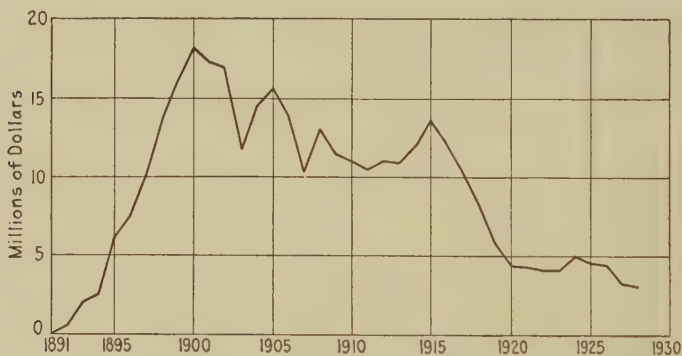


FIG. 100.—Curve showing the production of gold, by years, in the Cripple Creek, Colorado, district from 1891 to 1928. (Data from *U. S. Mineral Resources*.)

feet. Gold was found in the area at intervals between 1880 and 1890, but the first mining claim located there was in February, 1891. Shortly afterward, W. S. Stratton came into the district and, after considerable prospecting, located (on the Fourth of July) the Independence and Washington claims. Assays which he had made of the ore showed \$380 worth of gold per ton. Mining began at once, and the development was so rapid that the district reached its maximum production in 8 years (see Fig. 100).

Geology of the District.—The geology of the district is comparatively simple. The pre-Cambrian igneous and metamorphic rocks of the area were broken open by a violent volcanic eruption in Tertiary times. The material blown out formed a cone several miles in diameter and also finally filled the throat of the volcano. Erosion has removed most of the cone and exposed the neck made by the explosion. This neck, which is 3 miles wide and 5 miles long, consists of a breccia made up of fragments of phonolite (felsite), granite, gneiss, and schist (see Fig. 101). The breccia is porous and contains a great deal of water. The breccia and the surrounding rocks are cut by dikes and other intrusive masses. The intrusives consist of many kinds of igneous rocks, but the most abundant one is phonolite.

Mineralogy of the Ores.—The Cripple Creek district is one of the few localities where gold occurs in combination with another element. The chief ore mineral is *calaverite*, a gold telluride. The chief gangue minerals are quartz and fluorite. Small amounts of pyrite, sphalerite, and rarer sulfides are present, also. The upper parts of the veins have been slightly oxidized, a little of the telluride being broken up to form native gold.

Mode of Occurrence of the Ores.—The gold ores occur chiefly as *veins or lodes* and *replacement bodies*. The veins are mainly within the breccia of the neck, and the replacement deposits are usually in the granite. The veins are nearly vertical and show a slight radial arrangement. They are thin, and the lodes are really a series of essentially parallel thin veins (Fig. 102). Though some rich veins continue to great depths, the veins are usually more numerous and richer near the surface. The gold values occur in ore shoots within the lodes. Some of these shoots have been extraordinarily rich. Most of the lodes are only a few feet wide, although a few have a width of 50 feet. The replacement ores in the granite have developed near veins where the solutions could penetrate the wall rock.

Origin of the Ores.—The minerals in the Cripple Creek ores are believed to have been deposited

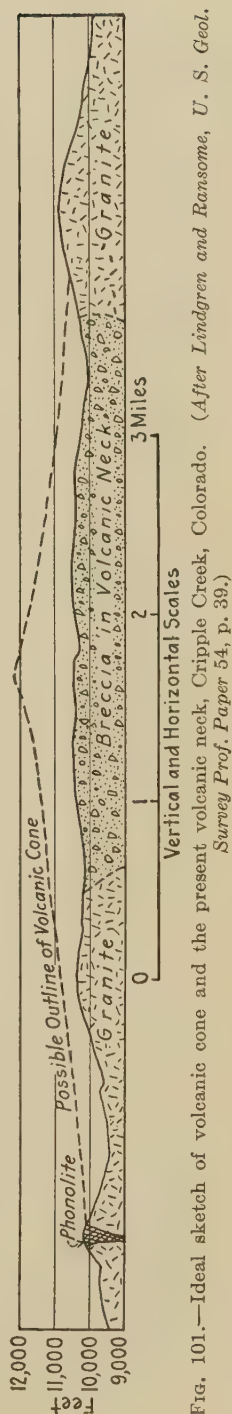


FIG. 101.—Ideal sketch of volcanic cone and the present volcanic neck, Cripple Creek, Colorado. (After Lindgren and Ransome, U. S. Geol. Survey Prof. Paper 54, p. 39.)

by hot solutions that had their source in a deep-seated magma. The ores were deposited soon after the last dikes were intruded. The period of mineralization was relatively short. The presence of sufficient tellurium to unite with all the gold in the solutions is the most remarkable feature of the origin of these deposits, as gold telluride ores are comparatively rare.



FIG. 102.—Section of Legal Tender vein or lode of Golden Cycle mine, level 10, Cripple Creek, Colorado. The country rock is a breccia oxidized along the seams. Main clay seam (rich ore) assays 300 ounces (over \$6,000) per ton. All seams (veins) carry values. (After Lindgren and Ransome, U. S. Geol. Survey Prof. Paper 54, p. 160.)

Production, Mining, and Tenor of the Ores.—The Cripple Creek district reached its maximum yearly production in 1900. The value of the gold it produced that year was \$18,000,000. Figure 100 shows the production there from 1891 to 1928. The value of the gold produced in the district during this period was \$344,243,083. During the period of maximum production, the ores were of high grade, averaging about \$30 per ton. Ores containing values of less than \$12 a ton were not mined. In 1927, the average value of the ore mined was \$6.75 per ton.

Pumping the water from the porous breccia in which the mines are located was expensive, so a drainage tunnel about 3 miles long was driven under the mines. The deeper mines are now (1928) below the level drained by the tunnel. Water from these deeper levels is pumped up to the tunnel and flows out through it.

JUNEAU DISTRICT, ALASKA

The most important gold mines of Alaska are in the vicinity of Juneau, in the southeastern part of the territory. The first gold deposits (now the Juneau mine) were discovered in this district in 1880 on the southeast side of Gold Creek, a little over 2 miles east of Juneau.

The next year, the deposits of the famous Alaska Treadwell group of mines were discovered on Douglas Island, across the narrow Gastineau Channel from Juneau. The Alaska Juneau mine has been productive almost continuously since 1880. In 1926, it was stated in *Mineral Industry*¹ that this was "the largest low-grade lode mine in the world." The company owning it ranked fourth in the list of gold-producing companies in the United States in 1927.

Geology of the Area.—The formations of the region consist of metamorphosed Paleozoic sedimentary and igneous rocks. The rocks are slates, schists, and greenstones. The metamorphosed sediments are cut by gabbro dikes and larger masses of diorite. The intrusion represented by the dikes occurred in post-Cretaceous times. The dio-

¹ P. 271.

rites represent a slightly later intrusion. The important ore-bearing formation is a black slate that dips steeply to the northeast (see Fig. 103).

Mineralogy of the Ores.—The gold occurs as *native gold* in pyrrhotite, quartz, and, to a lesser extent, pyrite. Other minerals present in the veins are sphalerite, galena, and calcite, and, less abundantly, chalcopyrite, arsenopyrite, dolomite, and siderite.

Mode of Occurrence of the Ores.—The ores occur in irregular quartz veins. Most of the veins are thin, only a few having a thickness of 5 feet. The majority of them are short, also. These irregular veins are connected by stringers of quartz, forming in this way such an intricate system of veins that the country rock (slates) must be mined as well as the veins. This has led to the adoption of a stoping method in mining, by which large quantities of ore can be handled cheaply.

The gold-quartz veins are irregularly distributed, some areas containing an abundance of them and other areas only a few. They occur throughout the slates and in the diorite dikes, also, although those in the dikes are rich enough to mine only where they are near the gold veins of the slates.

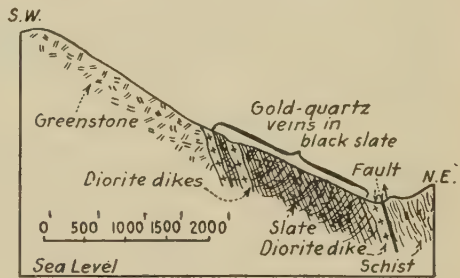


FIG. 103.—Diagram showing the geology of the Alaska Juneau gold mine, Juneau, Alaska. The gold-bearing lode is the zone of black slate with its quartz veins. (Modified after Spencer, U. S. Geol. Survey Bull. 287, p. 71.)

Origin of the Ores.—Spencer regards the deposits of the Juneau region as being of undoubted magmatic origin. He thinks that the hot solutions were derived from a deep-lying igneous mass that was probably dioritic in character. The solutions altered the diorite of the dikes to a certain extent but did not greatly change the slates. The veins were formed at a depth of 6,000 to 8,000 feet below the surface.

Production and Mining.—Up to 1927, the company controlling the Juneau mine had produced about 11,000,000 tons of ore which averaged \$0.87 worth of gold per ton. Total operating costs in 1926 were \$0.4875 per ton of ore. It is of interest to note that in 1903 the ore produced from this mine contained \$1.50 worth of gold per ton and that the operating costs were \$0.80 per ton. The mine has a capacity that enables it to handle 12,000 tons of ore per day; 3,829,000 tons was mined from it in 1926.

For many years, the Alaska-Treadwell mines were the largest producers in the district, but they were being worked under the channel, and water broke in and ruined them.

NOME, ALASKA

Nome is located on the south side of Seward Peninsula, Alaska. The placers of this area were discovered late in 1897, and the next year's development caused a "gold rush" in 1899. The district reached its maximum yearly production (more than \$7,000,000 worth of gold) in 1907. It was thought that the placers were exhausted some years ago, but the area ranked thirteenth among the gold districts of the United States in 1927.

The Beach Placers.—The gold placers at Nome are interesting because they are the result of wave action along a beach. No less than six beach placers have been found and worked. As these placers lie at different levels, it is evident that the shore in the region has moved up and down. The beaches have the following distribution:

Beach	Number of feet above sea level
Third.....	78
Second.....	38
Intermediate.....	22
Present.....	At sea level
Inner submarine.....	20
Outer submarine.....	34

The gravels vary much in their gold content. The bonanzas of the earlier periods have long ago been exhausted. Most of the gold consists of fine particles. The gravels are mined in the winter and washed in the summer time when the necessary water is available. Dredges are the chief means of recovering the gold.

Source of the Gold.—It is believed that the gold of the placers was derived from veins that occur inland and to the north of the deposits. Materials found in the gravels have been proved to have their source in this inland region, which supports the view that the gold came from the same area.

JARBRIDGE DISTRICT, NEVADA

The Jarbridge district lies in the northern part of Elko County, Nevada, near the Nevada-Idaho state line. Gold was discovered there late in the summer of 1909. As soon as news of the discovery had spread, there was the usual rush to the district, even though it was winter time. Essentially all of the important mines now (1928) worked were staked out and opened during the first year of the camp's development.

Geology of the Area.—The basement rocks of the district are Paleozoic sediments. These rocks were folded and then intruded by batholithic masses of granodiorite, probably during the Cretaceous era. A

period of erosion followed, and then great flows of felsitic lava (rhyolite) poured out over the surface until they were nearly 6,000 feet thick. Near the end of the Tertiary age, another rhyolite flow broke through the first ones and covered a wide area.

Mineralogy of the Ores.—The chief ore mineral of the deposits is *native gold*, but some silver is present (about one ounce per ton of ore). Electrum, argentite, and cerargyrite represent the silver compounds in the ores. Pyrite occurred in the primary sulfides, but in the oxidized deposits it has largely disappeared. The chief gangue minerals are quartz and adularia (a variety of orthoclase that occurs in veins). The former is the more abundant of the two gangue minerals and carries most of the gold. Numerous other minerals are present in the veins, which commonly contain fragments of the country rock, also.

Mode of Occurrence of the Ores.—The deposits of the district are typical gold-quartz fissure veins, that have developed, for the most part, along normal faults. The ores occur largely in crushed portions of the veins. As a rule, the latter have sharp walls. Their width is from 1 to 30 feet, and their length from a few hundred feet to several miles. Some veins have a vertical range of over 2,000 feet. The veins are confined entirely to the rhyolite but may extend downward into the Paleozoic sediments. They occur roughly in two belts, one on the west side and the other on the east side of a range of mountains known as the "Crater Range." The veins on the west side dip to the east, and those on the east side to the west, and all dip at high angles.

Origin of the Ores.—The ores of the veins were deposited by solutions coming from some deep-seated source. They rose along the fault planes of the area. The first solutions to rise deposited a group of minerals of which, with the exception of some remnants of calcite, only pseudomorphs are to be found. The later solutions, carrying the gold, silver, and other substances, replaced this first group of minerals with the present minerals. The hot solutions greatly altered the vein walls.

GOLDFIELD, NEVADA

The Goldfield district is located in the eastern part of Esmeralda County in southern Nevada. It is about 28 miles south of Tonopah. Although, at present (1928), the district is only a small producer of gold (essentially all the production comes from the reworking of an old tailings pile), it is of much historical interest. Gold was discovered there in 1903; and, by the end of 1904, the district had produced over \$2,350,000 worth of gold (and a little silver) from an ore that averaged \$316.60 per ton. Many ores found in the veins contained from \$6,000 to \$7,000 worth of gold per ton. Much difficulty was encountered in preventing the miners from stealing ("high grading," they call it) the rich ore. It is estimated

that by the end of 1907 fully \$2,000,000 worth of ore had been stolen from three rich mines alone. Theft was finally stopped but not until after the mines had been closed by a strike. The total production at Goldfield is about \$90,000,000 worth of gold. In 1926, only \$45,000 worth of gold was recovered from actual lode mining.

Geology of the Area.—The oldest rocks of the district are metamorphosed sediments, probably of Cambrian age. These rocks were intruded by granitic masses in late Jurassic times. A period of erosion followed, and then the area was buried under Tertiary lavas of which there are several varieties. The general structure of the district is that of a low dome the crest of which has undergone considerable erosion.

Mineralogy of the Ores.—The chief ore mineral is *native gold*, found in the primary sulfide ore and in the oxidized ores. The chief gangue mineral is quartz. It is accompanied by pyrite (in the sulfide ores) and alunite, which is a hydrous potash-alumina sulfate that has resulted from the alteration of the feldspar in the dacite and is especially common in this district. Many other minerals are present in minor quantities.

Mode of Occurrence of the Ores.—The ores of the district are gold-bearing siliceous bodies that have been developed along fissures by the alteration of the wall rock. The silicified bodies (called "ledges") are very irregular. The gold is distributed through them as shoots, which are likewise irregular. The ledges are confined to one type of lava, a dacite (felsite). The dacite is about 600 feet thick, and no veins occur below it.

Origin of the Ores.—The Goldfield ores are believed to have been deposited by hot solutions derived from an underlying mass. These solutions contained an abundance of hydrogen sulfide and, of course, the gold and other metals. Where they came close to the surface, the hydrogen sulfide in them was oxidized to sulfuric acid, which attacked the feldspar and altered it to alunite. Some of the silica liberated in this process formed a part, at least, of the quartz in the ores.

SILVER DISTRICTS

In 1927, 25 mining companies in the United States each produced over 600,000 ounces of silver. Their total production was 38,700,000 ounces, which was 65 per cent of the total silver production of the country. Gold is usually present, in some degree, in these ores, but silver is the dominant metal. Table 48 shows the complex ores that are the source of silver, and their relative abundance in the United States. In the deposits of the 25 companies, silver is associated with lead in no less than 17 deposits, a fact in keeping with the common occurrence of argentiferous galena. It should be noted also that only 4 of these companies produce silver from dry and siliceous ores unassociated with lead, copper, and zinc.

TABLE 48.—TYPES OF ORES CONTAINING SILVER, AND NUMBER OF MINING COMPANIES PRODUCING EACH IN THE UNITED STATES¹

Number of companies	Ores					
	Siliceous	Lead	Copper	Zinc	Lead-zinc	Copper-lead
4	X					
3	X	X			X	
3			X			
3		X				
2		X	X		X	
2		X			X	
2	X	X				
2		X	X			
1			X	X		
1			X		X	
1						X
1					X	

¹ Data U. S. Mineral Resources, 1927, Part 1.

UTAH SILVER DISTRICTS

Utah has led all the states of the Union in the production of silver for the last 8 years (1921 to 1928). Of the 25 leading silver-mining companies in the United States in 1927, 9 were located in Utah; 3 of them were in the Tintic, 2 in the Park City, and 4 in the Bingham Cañon districts. In 1928, the total silver production of Utah was 16,682,000 ounces, valued at \$9,759,000. This was a decrease from the preceding years. From 1864 to 1928, Utah produced a total of 546,071,541 ounces of silver. The silver comes dominantly from lead ores but also from dry and siliceous, copper, lead-zinc, and zinc ores.

TINTIC DISTRICT, UTAH

The Tintic mining district is located in two counties, Juab and Utah, in the East Tintic Mountains of central Utah. The ores of the district were discovered in 1869. The area is one of the most important producers of silver and lead in the United States, and it is responsible for an important production of other metals, also, as is seen from the following table:

TABLE 49.—TOTAL PRODUCTION OF THE VARIOUS METALS IN THE TINTIC DISTRICT, 1869-1928¹

Metal	Quantity produced
Gold.....	1,900,919 oz.
Silver.....	210,872,067 oz.
Copper.....	210,337,522 lb.
Lead.....	1,449,024,149 lb.
Zinc.....	28,990,765 lb.

¹ Data from U. S. Bur. Mines.

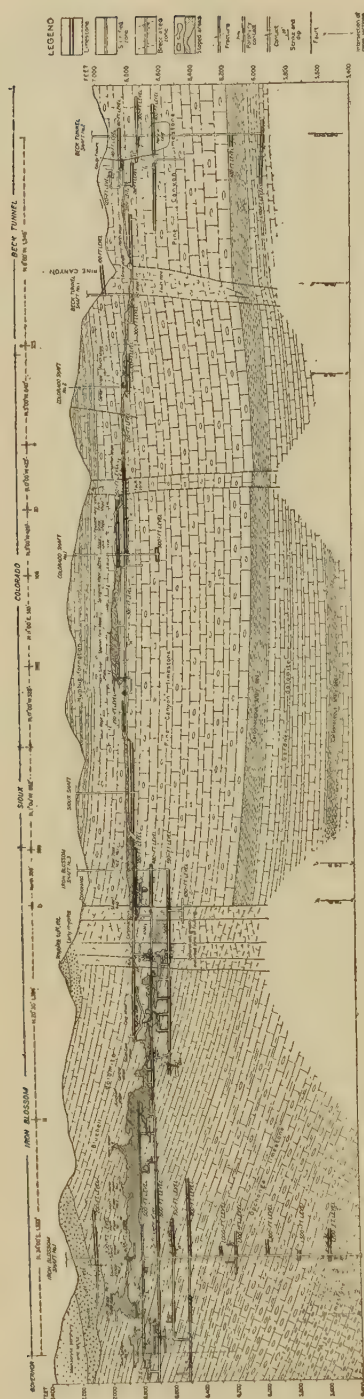


Fig. 104.—Exceptionally long (8,263 feet) replacement ore body in Tintic district, Utah. (Lindgren and Loughlin, U. S. Geol. Survey Prof. Paper 107, pl. 36.)

Three companies of the Tintic district: the Tintic Standard, the Plutus, and the Chief Consolidated, were among the 25 leading silver-producing companies in the United States in 1927. The Tintic Standard has one of the richest silver mines in the United States.

Geology of the Area.—The rocks of the area are strongly folded and faulted Paleozoic sediments. They consist of 6,000 feet of quartzite, below 6,500 to 7,000 feet of limestone with some shale. In Tertiary times, lavas spread far and wide over the area, and, later, a small mass of monzonite was intruded into the earlier rocks.

Mineralogy of the Ores.—The primary ore minerals of the veins in the igneous rocks and adjacent limestones are *pyrite*, *enargite*, and a little galena and sphalerite. Chalcedony (jasperoid), quartz, and barite are the common gangue minerals. These are not good silver-lead ores.

The chief primary ore minerals of the replacement bodies in the limestone are *galena*, *pyrite*, *enargite*, and *sphalerite*. The gangue minerals are the same as those of the veins. The silver, as *argentite*, is present in the galena and also in the pyrite. The ores are siliceous throughout most of the mines, but, locally, the massive galena and the lead carbonate ores are not. The minerals of the oxidized parts of the deposits are *argentite*, *cerargyrite*, *native silver*, and some *cerussite* and *anglesite*.

Mode of Occurrence of the Ores.—The ores occur in both the

igneous and sedimentary rocks but are far more abundant in the sediments. The deposits in the igneous rocks are *fissure veins*; those in the sedimentary rocks are *replacement bodies* having a wide range in shape and size. Striking features of the replacement deposits are their horizontal position and the absence of fissures in connection with them. Some of the ore bodies are remarkably long; one has been mined continuously for 7,000 feet (see Fig. 104) and can be traced for an additional 4,000 feet. Another has been mined for 8,000 feet horizontally and, at one end, for over 1,000 feet vertically. These elongated bodies are from 4 to 50 feet wide and up to 150 feet thick. Not all the ore bodies are horizontal, however, some being inclined or vertical.

The ores show a somewhat zonal arrangement. Copper is more abundant near the monzonite intrusive, and the lead and silver at a distance from it. Considerable alteration of the monzonite occurred adjacent to the veins. Oxidation has extended to unusual depths—in some deposits, to 2,000 feet or more.

Origin of the Ores.—The mineralizing solutions that formed the ores evidently came from the deeper portion of the monzonite intrusive. The solutions were only moderately hot (100 to 300°C.), and the deposits were formed at distances between 1,500 and 3,000 feet of the surface. Two phases of mineralization occurred. The first consisted in the replacement of limestone and dolomite by colloidal silica that slowly crystallized as chalcedony or jasperoid. Barite, pyrite, galena, and other minerals were formed also. The minerals of the second phase of mineralization were deposited in irregular openings within the jasperoid and consist of more barite and large quantities of galena and other ore minerals.

PARK CITY, UTAH

The Park City district is in the Wasatch Mountains, about 25 miles southeast of Salt Lake City, Utah. It lies in three counties, Summit, Wasatch, and Salt Lake, though the productive mines are only in the first two. The ores of the region were discovered in 1870, and the district has been active in production ever since, though many changes have taken place, such as old mines' becoming exhausted and new ones opened. At present (1928), there are two major divisions of the district; but, as essentially all the production is made by two large mining companies (the Park Utah Consolidated and the Silver King Coalition), both of which operate in different parts of the area, the subdistricts, as such, will not be discussed here. The total silver production from 1870 to 1928 amounted to 188,990,448 ounces. As in the Tintic district, however, silver is not the only metal produced. The following table shows the total production of each metal from 1870 to 1928:

TABLE 50.—TOTAL PRODUCTION OF VARIOUS METALS OF THE PARK CITY DISTRICT, 1870-1928¹

Metal	Production
Gold.....	350,634 oz.
Silver.....	188,990,448 oz.
Copper.....	50,280,718 lb.
Lead.....	1,814,775,231 lb.
Zinc.....	238,390,557 lb.

¹ Data U. S. Bur. Mines.

A glance at these figures is sufficient to indicate that, although silver and lead predominate, the ores of the district are really complex mixtures of five metals.

Geology of the Area.—The formations of the district consist of pre-Cambrian metamorphic rocks and Paleozoic and early Mesozoic sediments all of which have been subjected to intrusions. The intrusive rocks are quartz diorite and quartz diorite porphyry. The ore bodies are confined to the Carboniferous and later formations. The region was folded and faulted in Cretaceous times, and the intrusions followed shortly afterward. Extensive contact metamorphism accompanied the igneous activity.

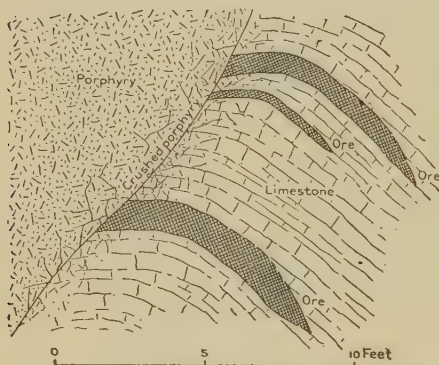


FIG. 105.—Bedded ore in limestone adjacent to intrusive, cut by fault of postintrusive and postmineral date, Kearns-Keith mine, Park City, Utah. (Boutwell, U. S. Geol. Survey Prof. Paper 77, Fig. 6, p. 104.)

Mineralogy of the Ores.—The chief ore mineral in the district is *argentiferous galena* (the silver is probably present as argentite), and *tetrahedrite* is next in importance. *Sphalerite* is fairly abundant in some ores, but pyrite and chalcopyrite are rare in all. Gangue minerals are present in very minor amounts, the ore being solid masses of the sulfides. Oxidation has formed numerous carbonates, sulfates, and oxides from the sulfides.

carbonates, sulfates, and oxides from the sulfides.

Mode of Occurrence of the Ores.—The ores occur as *lodes* and *replacement bedded deposits*. Both furnish valuable high-grade ore.

The *lode deposits* are extensive and persistent and cut both sedimentary and igneous rocks. In general, they strike a little north of east and are several thousand feet long. The upper portions are the richer, but the lower contain the greater quantity of ore.

The *bedded deposits* contain the rich ores of the district. The deposits occur in various sediments, but the richest ores are in the Park City (Carboniferous) and Thaynes (Triassic) limestones. The bedded deposits are closely associated with the dioritic intrusives. They are lenticular in

shape and are essentially parallel to the bedding (Fig. 105) of the enclosing limestone. They range from a few inches in thickness to 6 or rarely 10 feet, and they extend for several hundred feet along the strike of the beds and as much as 150 feet down the dip. They consist dominantly of sulfides, which furnish the bonanza ores.

Origin of the Ores.—The ore deposits of Park City were formed by hot solutions that were derived from the dioritic parent magma. The solutions effected considerable contact metamorphism in the limestone encountered.

BINGHAM CAÑON, UTAH

The Bingham Cañon district has been described as a copper district (p. 167), so the discussion here will deal only with the silver ores.

The Deposits.—In the Bingham Cañon district, the silver is recovered from dry and siliceous, lead, lead-zinc, and copper ore. The first three types of ore occur northwest (in the West Mountain area) of the great disseminated copper deposit. The ores are in Carboniferous formations, which consist of a great series of quartzite (containing numerous beds of limestone) and calcareous shales. The Highland Boy, Jordan, and Commercial limestones contain the best ore bodies. These rocks, especially the limestones, have undergone considerable contact metamorphism. The large copper ore body in the Highland Boy mine is a replacement of the limestone of the same name.

The silver-lead ores are found in lodes that follow strong fissures. The vein deposits are in all types of rocks, but they are largest and richest where they cross the limestones. The chief ore mineral is *silver-bearing galena*, but there are also some *tetrahedrite*, *chalcopyrite*, *sphalerite*, and *pyrite*. The gangue minerals are quartz, calcite, some barite, and rhodochrosite.

Production of the Various Ores.—The production and composition of the silver-bearing ores mined in Bingham Cañon in 1926 are shown in the following table:

TABLE 51.—PRODUCTION OF THE VARIOUS METALS FROM ORES IN THE BINGHAM CAÑON DISTRICT, 1926¹

Kind of ore	Number of producing mines	Ore, short tons	Gold, ounces	Silver, ounces	Copper, pounds	Lead, pounds	Zinc, pounds
Dry and siliceous.....	8	1,349	402.28	7,369	15,714	10,275	
Lead.....	18	99,658	6,570.57	774,769	2,175,333	27,648,045	
Lead-zinc....	13	498,713	20,892.43	1,733,299	3,223,235	81,902,167	50,762,818

¹ U. S. Bur. Mines.

SHAFTER, TEXAS

The only production of the Shafter district comes from the Presidio mine, which is located at Shafter in Presidio County, southwestern Texas. The mine is not very well known but is important, the production in 1928 being about 1,391,000 ounces of silver, valued at \$813,908. This deposit was discovered in 1884, and production from it has been steady since 1885. The estimated total production of the mine is about 21,000,000 ounces of silver. The ores are reached through two shafts, one 400 and the other 700 feet deep. It is estimated that the mine contains over 25 miles of underground workings.

The ore occurs in irregular solution channels in the upper part of a limestone of Upper Carboniferous age. The ore bodies vary in size and shape and are connected by thin stringers. The ore consists of *cerargyrite*, or horn silver, in a quartz gangue. Occasional pockets of silver-bearing galena are found, and a little galena is scattered all through the ore. Calcite is also fairly common, and sphalerite, cerussite, and malachite occur. Dikes of basic igneous rocks have been encountered in the mine, but evidently the ores have no connection with them. Deeper-lying intrusives were probably the source of the original ores, which apparently were argentite and some galena. The argentite has been converted into the chloride (*cerargyrite*) by the surface waters of the arid region. These solutions found their way underground through the numerous solution channels.

OTHER SILVER DISTRICTS

Silver is produced in many other districts throughout western United States. These districts are in Colorado, Idaho, Arizona, Nevada, and California. The history of a mine or a district is a record of discovery, flush production, a period of slow decline (see curve of Cripple Creek's production, Fig. 100), and the final closing of the mine or district. Many, many silver mines have gone through this sequence of events; many of 25 years ago are not worth mentioning today as economic projects.

GOLD-SILVER DISTRICTS

The preceding accounts of gold and of silver districts cover the most important producing areas of these metals in the United States today (1928). Actually, a little silver occurs in the gold deposits, and a little gold in the silver, for neither metal is found entirely free from the other. There is a small number of districts in this country, however, in which both gold and silver occur in somewhat equal quantities. It is a curious fact that few of these districts are economically important at present. They will be discussed briefly.

COMSTOCK LODE DISTRICT, NEVADA

The Comstock Lode district has been world famous. The lode was discovered in 1859 and has produced approximately \$400,000,000 worth of gold and silver in the ratio of 2 parts gold to 3, silver. The climax of its production has long since passed, and the district now (1929) makes only a nominal production. The history of its early days portrays the romance of mining at its height.

The ores occurred in a great lode, about $2\frac{1}{2}$ miles long, that developed along a fault fissure. In places, the lode was several hundred feet wide. The solutions that deposited the ores greatly altered the various igneous rocks forming the walls of the fissure. The ore minerals were *native gold* and *argentite* and other silver minerals in a broken mass of quartz and calcite. Some pyrite, galena, sphalerite, and chalcopyrite also occur. Enormously rich bonanzas were found here and there along the lode, but on account of their great size and irregularity great difficulty was experienced in mining them, a fact which finally led to the development of the square-set system of mining. The mining has extended downward about 3,000 feet, but the very large volume of hot water [maximum temperature, 77°C. (170°F)] encountered at the greater depths makes work very difficult.

TONAPAH, NEVADA

Although still fairly productive, the Tonopah district in Nye County, Nevada, has long since passed its zenith. The ores of the district were discovered in 1900, and by 1927, \$34,134,700 worth of gold and 155,840,652 ounces of silver (total value of gold and silver, \$133,989,000) had been produced from them.

The ores are in a complex, faulted series of lava flows. Faulting and fissuring occurred both before and after they were deposited. They occur in typical quartz veins, that are usually narrow but rarely may be 20 feet or more wide. The ore minerals are *native gold* and *argentite* and other silver minerals. Minor amounts of other sulfides are found, and various carbonates occur as gangue minerals. Hot magmatic solutions deposited the ores and extensively altered the lavas adjacent to the veins.

EUREKA, NEVADA

The ores of the Eureka district in Nevada were discovered in 1869, and since then the area has produced about \$70,000,000 worth of gold and silver. The ores are replacement masses of irregular character and occur in Paleozoic limestones. The usual group of common sulfides occurs, and these contain the gold and silver. The ores were deposited by solutions derived from magmas which are now represented by nearby intrusive granitic porphyries. The ores have been strongly oxidized, and considerable secondary enrichment has occurred.

ASPEN, COLORADO

The Aspen silver-lead camp of Colorado rivaled the Leadville district in fame during its most productive period in the early nineties. The Aspen ores were discovered in 1879, a year after the rich silver ores at Leadville had been opened; but the production was small until about 1888 when two railroads reached the camp. During recent years, considerable zinc has been produced in addition to silver and lead.

The sedimentary formations are Paleozoic and Mesozoic in age. The beds have been intensely folded and faulted and are cut by porphyry intrusives. The ores are dominantly in Carboniferous rocks and occur as veins and replacements in a limestone which lies below an impervious shale. The deposits lie at the intersection of a series of fault planes. There are three types: barite, silver-lead, and galena-sphalerite veins. The silver-lead veins contain much polybasite, Ag_3SbS_6 , but native silver and some other minerals also occur. A mass of native silver—from 0.5 inch to 2.5 feet thick, 3 to 4 feet wide, 20 to 30 feet long, and weighing 1,340 pounds—was found in the Smuggler mine (a very famous mine in the district). The chief gangue minerals of the deposits are quartz, barite, and dolomite. The ores are believed to have been formed by magmatic waters that came from an igneous mass below. Some believe that the deposits have undergone secondary enrichment, but Spurr, who studied the district in detail, does not.

SAN JUAN REGION, COLORADO

The San Juan region includes parts of several counties in southwestern Colorado (see Fig. 106). There are a number of mining districts within the area, the most notable being Ouray, Telluride, Rico, Silverton, Eureka, Lake City, and Creede. The region contains many mountains of which the central group is the San Juan Mountains.

The geological formations are from pre-Cambrian to Recent in age. The Paleozoic and Mesozoic rocks were folded and eroded before the Tertiary era, and during the Tertiary intense volcanic activity occurred. At least 6,000 to 8,000 feet of lava flows and tuff beds accumulated. Numerous igneous intrusions in the form of dikes, sills, and laccoliths occurred at various intervals. The intrusive rocks are monzonites, diorites, and various porphyries. All these rocks were extensively faulted near the end of the Tertiary era. Since then, the area has been deeply dissected by erosion.

The ore deposits of the region are dominantly well-developed and persistent fissure veins. Some of these veins can be traced for miles and have a vertical dimension of 4,000 feet. Other types, such as replacements, bedded deposits, and pipes, occur, but they are only locally impor-

tant. The veins are usually banded and show both comb and colloform structures. For the most part, they are only a few feet wide. Most of them were deposited in the shallow vein zone, but, due to their great persistence vertically, they grade into those of the deeper zones. The veins are filled fissures showing no relationship to the country rock. The wall rock has undergone very little alteration.

The ores of the district are primarily silver-lead-gold, but large tonnages of more complex ores occur; and, as these can now be successfully treated, the production of copper and zinc has increased in recent years. The gold occurs largely as *native gold* (more rarely as the telluride)

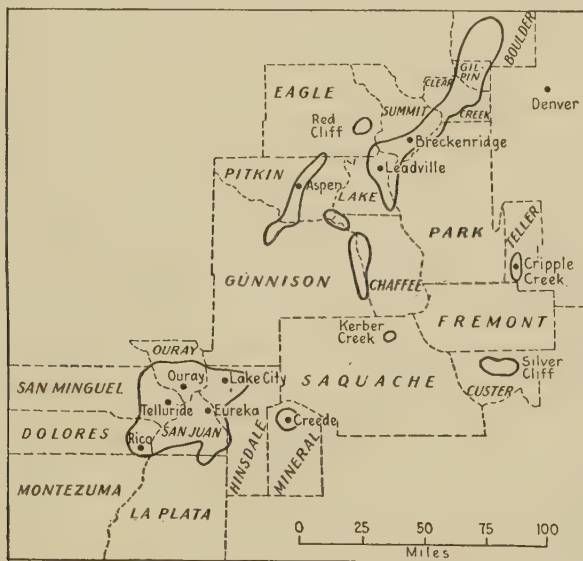


FIG. 106.—Map showing the location of the important mineralized (gold, silver, lead, zinc, copper) areas of Colorado. (Modified after Spurr, U. S. Geol. Survey Mon. 63, pl. 18, p. 128.)

in gold-quartz veins; and the silver, as *silver-bearing galena*, *argentite*, and other silver-bearing minerals. The complex ores consist of galena, chalcopyrite, pyrite, sphalerite, argentite, tetrahedrite, and some rare minerals. Quartz is by far the most common gangue mineral, but barite, rhodochrosite, calcite, dolomite, rhodonite, and fluorite also occur. Oxidation has taken place in minor amounts.

There is little doubt but that the ores of the San Juan region were deposited by solutions having their source in a magmatic mass below. The ore and gangue minerals were deposited chiefly in the fissures; but, where the physical conditions were favorable, they formed replacement and other types of deposits.

LAKE COUNTY-Boulder COUNTY REGION, COLORADO

An important mineralized belt extends from Leadville in Lake County northeast to the northern part of Boulder County, a distance of about 85 miles (Fig. 106). The belt follows the main range of the Rocky Mountains. It includes many districts some of which are Leadville, Red Cliff, Breckenridge, and Georgetown.

The rocks of the belt from Boulder County to near Breckenridge in Summit County are pre-Cambrian igneous and metamorphic ones that are cut by intrusives of monzonite porphyry (Tertiary age). In the southwest end of the belt, the pre-Cambrian rocks lie beneath Paleozoic and Mesozoic sediments, which are also cut by igneous rocks. The deposits in the northeast end of the district (already described) are dominantly typical filled-fissure veins, but those to the southwest (from Breckenridge to Leadville) include replacement deposits in sedimentary rocks.

The ores of the northeast part of the district, contain, in Clear Creek County, mainly silver; in Gilpin and Boulder counties, principally gold. The chief ore minerals in the *silver veins* are galena, sphalerite, pyrite, chalcopryite, and tetrahedrite. Quartz is the chief gangue mineral, though siderite, calcite, fluorite, and barite are common, also. Not all of these minerals are necessarily present in each district. The sulfides in the *gold veins* are pyrite, chalcopryite, and minor amounts of others. Quartz is the chief gangue mineral, and a little calcite and siderite are present.

All the deposits of this region are of magmatic origin. The ore deposition occurred not long after the time of the igneous intrusions.

PRINCIPAL FOREIGN GOLD AND SILVER DEPOSITS

Gold and silver deposits are found in many parts of the world, as shown by Figs. 107 and 108. In 1927, the countries leading in the production of gold were South Africa, the United States, Canada, Russia (including Siberia), Mexico, and Australia; and of silver, Mexico, the United States, Canada, Peru, and Australia. The foreign deposits can be treated only briefly here.

THE TRANSVAAL, SOUTH AFRICA

The gold production of the "Rand," as the Witwatersrand district is commonly called, exceeds that of all the other districts of the world. In 1927, it amounted to 57 per cent of the total gold production of the world and was five times as large as that of the United States, which was the country whose production was next to that of the Transvaal. The Rand district is located near the city of Johannesburg in southern Transvaal. The deposits were discovered in 1885, and mining began in 1887.

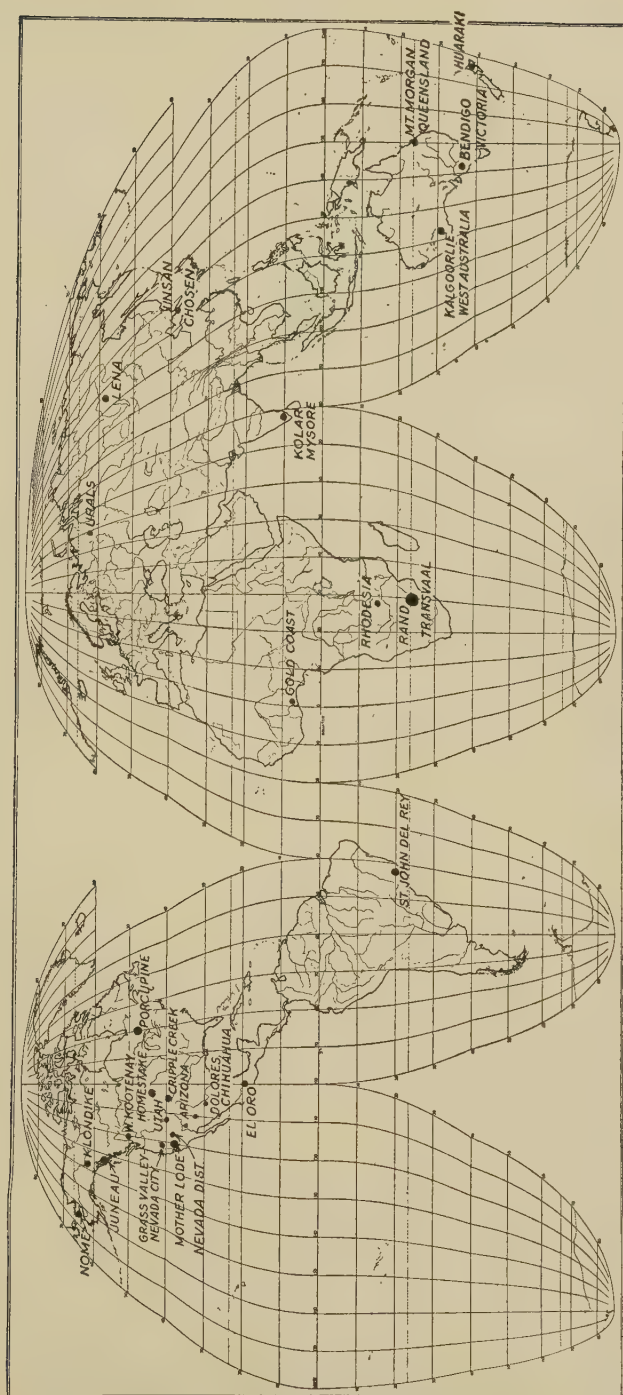


FIG. 107.—Important gold deposits of the world (1928).

Geology of the Area.—The rocks of the area include a great series of pre-Cambrian, and the Karroo system of Permian-Carboniferous age. The gold occurs in the Witwatersrand system (probably pre-Cambrian) of conglomerates, quartzites, and slates. This series is about 19,000 feet thick. These rocks have been folded into a syncline that strikes a little north of east and is about 120 miles long and 45 miles wide. The gold deposits are on the north limb of the syncline and lie adjacent to the ancient granites of the Swaziland system to the north. The Lower Witwatersrand series consists of resistant slates and quartzites the up-turned edges of which stand out as a prominent ridge or escarpment, locally known as the "Rand" from the Dutch word *rand*, which means "edge." The escarpment lies north of Johannesburg. The formations dip steeply (about 50°) to the south along the north limb of the syncline but flatten out with depth.

Mode of Occurrence of the Ores.—The gold (as *native gold*) occurs disseminated through conglomerates in the Upper Witwatersrand series. There are several gold-bearing horizons, but only the Main Reef group near the base of the series is extensively worked. (The tenor of the ores in the higher conglomerates is low, usually less than \$3 per ton.) The Main Reef group is about 90 feet thick and is worked for a distance of about 50 miles along the northern outcrop. Where the beds reappear on the south side of the syncline, the amount of gold they contain is insignificant. The beds of the Main Reef from top to bottom are listed below:

	Thickness, feet
South Reef (productive).....	3
Bastard Reef (barren of gold).....	20 to 40
Main Reef Leader (richest).....	2
Quartzite (barren).....	2 to 20
Main Reef (productive).....	4

As seen from this list, the gold is confined to three beds: the Main Reef Leader, the Main Reef, and the South Reef. All of these beds are worked in the middle part of the Rand, but the Main Reef Leader disappears toward the west, and the other two disappear toward the east. The gold is not uniformly distributed through the conglomerates but follows shoots that pitch to the southeast.

The Main Reef conglomerates are composed dominantly of rounded quartz pebbles and some quartzite and slate pebbles. The pebbles are embedded in sand, and the whole has been cemented by quartz and chalcedony. About 3 per cent of the cement is iron sulfide (marcasite, according to Rastall¹), and the gold is associated with it as fine scales and crystalline flakes. Visible gold is rare.

Origin of the Deposits.—The origin of these remarkable gold deposits has long been, and still is, a matter of open discussion among geologists.

¹ RASTALL, R. H., "The Geology of the Metalliferous Deposits," p. 472, 1923.

As has been pointed out in the discussion of the lead and zinc deposits of the Mississippi Valley, a deposit of simple mineralogy is more difficult to explain than the more complex deposits, and the gold deposits of the Rand are apparently such.

One group of geologists regards these gold deposits as placers, citing as evidence (1) the typical association of the gold with conglomerates, (2) the rounded pebbles of iron sulfide (now known to be due to radial crystallization), and (3) the association of the gold with what were apparently water channels that furnished material for the conglomerates. Mellor emphasizes the delta-like arrangement of the gold shoots in the conglomerates.

Opponents of this view point out that the gold is crystalline and that magnetite and ilmenite do not occur with it in the conglomerates. They advocate the introduction of the gold and marcasite in solutions. This theory would account for the crystalline gold and iron sulfide, but there is little evidence as to a source of the solutions or channels for their entrance.

Probably both of these theories are partly correct in explaining the origin of these deposits. The occurrence and distribution of the gold in conglomerates certainly favor an origin as a placer deposit; and, after the placer had been buried (but while it was relatively near the surface), hot solutions could have been introduced into it which deposited the iron sulfide and chalcedony and recrystallized the gold.

Production, Tenor of Ore, and Mines.—The total production of the Transvaal district to the end of 1928 (a 41-year period) amounted to \$4,014,000,000 worth of gold. In 1926, studies of the ore reserves were made which indicate that the peak of production has nearly been reached. The output in 1926 was 29,000,000 tons of ore, and this amount is expected to decrease about one-half in 10 years and to less than one-fifth of the amount in 15 years.¹ The average tenor of the ore mined in 1926 was \$6.62 worth of gold per ton.

Some of the mines of the Rand are the deepest in the world. The Village Deep and City Deep mines have vertical depths of more than 7,000 feet. The temperature at 6,869 feet in the Village Deep mine is 35.5°C. (96°F.).

PORCUPINE AND KIRKLAND LAKE DISTRICTS, ONTARIO, CANADA

The very important gold deposits of Porcupine and Kirkland Lake are in northern Ontario (Fig. 109). They are of recent development, the first rich strike having been in 1909. Since then, the production of these districts has been over \$400,000,000 worth of gold. Several other smaller districts are in the area.

¹ *Mineral Industry*, 1926, p. 303.

The rocks are all very ancient, being composed of Kewatin greenstones, schists, and gneisses, and Huronian metamorphosed sediments. All of them are cut by dikes and stocks of quartz porphyries, granites, and syenites.

The gold deposits at *Porcupine* are *gold-quartz veins* in schist and *disseminated gold* in schists. The gold is mainly *free gold*, but some tellurides occur. Sulfides are not common in the veins but are quite abundant in the schists. At *Kirkland Lake*, the ores occur largely in faulted zones and fissures. Gold tellurides and some sulfides are found. The gangue minerals, which are calcite and dolomite, indicate that the veins were formed nearer the surface than were those at Porcupine. The ores of both districts were deposited by solutions from the numerous intrusions of igneous masses into the pre-Cambrian rocks.

COBALT, ONTARIO

Cobalt is located in northern Ontario, about 100 miles southeast of Porcupine and about 300 miles due north of Toronto (Fig. 109). The deposits of this district contain the richest silver ores that have been

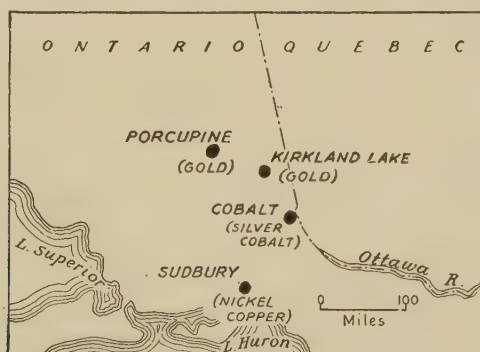


FIG. 109.—Map of eastern Ontario showing the location of important mining districts and minerals mined in them.

discovered in the twentieth century, and they are among the richest ever found. They were discovered in 1903 during the building of the Timiskaming and Northern Ontario railroad. Rich silver veins were found exposed at the surface. Masses of native silver were obtained that weighed over 1,600 pounds.

Geology of the Area.—The basal formations are Kewatin greenstones and schists containing some metamorphosed sediments. The Cobalt series of conglomerates and related sediments of Huronian age was deposited on beds of the Kewatin formation, and all were later subjected to intrusions. The intrusive rocks are diabase sills some of which are 1,000 feet thick.

Mineralogy of the Ores.—The silver ore mineral is *native silver*. It is associated in the veins with the cobalt-nickel ores, which consist of 10 or 12 cobalt-nickel arsenides. The veins may consist entirely of these minerals, or a little calcite gangue may be present.

Mode of Occurrence, Tenor, and Origin of the Ores.—The ores occur in well-defined veins found dominantly in the Cobalt series beneath a diabase sill and, to a lesser extent, in Kewatin beds and in the diabase itself. The majority of the veins are less than 300 feet long, but a few extend downward 1,000 feet or more. They are usually about 4 inches wide or less, but a few are 8 to 12 inches in width.

The tenor of much of the ore runs into thousands of ounces of silver per ton. A single vein, the La Rose, yielded from a section 100 feet long (and within 60 feet of the surface) 658,000 ounces of silver. This production shows the great richness of the deposits, especially when we remember how narrow the veins are.

The ores are believed to have been derived from solutions coming from the magma that produced the diabase sills.

SILVER AND GOLD DISTRICTS OF MEXICO

Silver Districts.—For centuries, Mexico has been one of the leading producers of silver. About 60 per cent of the production comes from three states: Hidalgo, at Pachuca about 70 miles north of Mexico City; Guanajuato, at Guanajuato 150 miles northwest of Mexico City; and Zacatecas. Mines occur to the northwest of this district and on through to the United States line.

The silver deposits of *Hidalgo* and *Guanajuato* occur as veins in Tertiary felsitic rocks (like those of Comstock Lode and Tonopah). The ore minerals are *argentite*, *polybasite*, *galena*, *pyrite*, *sphalerite*, and some other silver minerals. The gangue minerals are mainly quartz, rhodochrosite, rhodonite, and calcite. These deposits once contained great bonanzas, but the ore today (1928) is much lower in grade. The *Zacatecas* ores, though associated with the Tertiary felsitic rocks, occur largely as great replacement silver-lead deposits in limestones. Some vein deposits also occur in Zacatecas. These Mexican ores are of magmatic origin.

Gold Districts.—The chief gold district in Mexico contains the famous El Oro mine at El Oro in the northwestern part of the state of Mexico. The gold was discovered in the early part of the present century. The gold lodes are in a black slate that lies beneath Tertiary igneous rocks. The metal is finely divided *native gold*. The gangue minerals are dominantly quartz, with some calcite and a little pyrite and sphalerite. The lodes are mostly 3 to 15 feet across and average from \$5 to \$15 in gold and 2 or 3 ounces of silver per ton. The ores were deposited by rising solutions.

AUSTRALIAN GOLD DISTRICTS

Three important gold districts of Australia are the Bendigo district in Victoria, the Coolgardie goldfield in Western Australia, and Mount Morgan in Queensland.

The deposits of the *Bendigo district* are gold-quartz veins that follow the folding of the Ordovician slates and quartzites (so-called "saddle reefs"). The ores of the *Coolgardie goldfield* are lenticular replacement deposits occurring in metamorphosed sediments and igneous rocks. Some ore bodies are 100 feet wide. The primary ores consist of *gold telluride* and some sulfides. The gangue mineral is quartz. Portions of the deposits have been oxidized, and in them *native gold* occurs. One very rich part of this field, near Kalgoorlie, has been called the "Golden Mile." The *Mount Morgan* mine was originally a great gold mine. It is estimated to have produced \$100,000,000 worth of gold. The ore body is an oxidized replacement deposit in a limestone that is surrounded by granite. The lower limit of the rich gold ore was 160 to 300 feet below the surface. Below this depth, the ore was pyritic, but chalcopyrite becomes more abundant with depth, so the mine is now a copper mine, also. The ore contains 2 to 3 per cent of copper and from \$1 to \$8 worth of gold per ton.

SILVER DEPOSITS OF PERU AND BOLIVIA

The silver deposits of Peru and Bolivia are among the largest and most famous in the world. They had been worked by the natives of those countries long before the arrival of the Spaniards. The silver output of Bolivia from 1545 to 1927 is estimated at 50,000 tons of silver, and of Peru at 42,000 tons. Peru and Bolivia (and Chile) are a part of the great chain of silver districts that are located in the mountain belt extending from Canada, through western United States, Mexico, Central America, Colombia, Peru, and Bolivia, to Chile. This great belt produces about 75 per cent of the world's silver.

Deposits of Peru.—The Peruvian silver deposits occur in the north-western part of Peru, in the departments of Cajamarca, Libertad, Ancachs, Huanco, and Junin. The deposits cover an area about 550 miles long and 120 miles in width. Those of Cerro de Pasco in Junin department are the most famous ones. The ores occur in and adjacent to a stock of quartz monzonite that is intrusive in sediments and tuffs. The ores are complex and contain silver, lead, and copper. The chief gangue mineral is quartz, which is accompanied by varying amounts of carbonates and other minerals. The deposits were worked for silver (largely *cerargyrite* and *native silver*) at first, but in the deeper zones copper is mined. In other districts, the silver occurs with lead.

Deposits of Bolivia.—The Bolivian silver-tin deposits are in south-western Bolivia, in a belt extending from Oruro through Potosi to

Pulacayo, a distance of about 200 miles. Silver is the dominant mineral from Potosi to the south end of the area; and tin is abundant from Potosi to the north end and on beyond almost to La Paz. Silver was the first mineral mined in the district. There are many mines in the area, but those of Potosi are the most famous. It is estimated that they have produced over 30,000 tons of silver since 1545, more than that produced from any other one deposit in the world.

The geology of the area is simple. Monzonites cut Paleozoic slates and quartzites; and the ore veins, which are replacements along fissures, occur in all the rocks. The ores are dominantly pyrite, arsenopyrite, cassiterite, sphalerite, and *ruby silver*. Quartz is the chief gangue mineral. The oxidized parts of the ores were rich in silver minerals, notably *native silver* and *cerargyrite*, which become less abundant below. The tin increases in abundance downward. The mines are only about 2,000 feet deep.

GOLD DEPOSITS OF BRAZIL

The only important gold deposit in Brazil is that of the very famous Morro Velho mine at St. John del Rey in Minas Geraes, about 200 miles northwest of Rio de Janeiro.

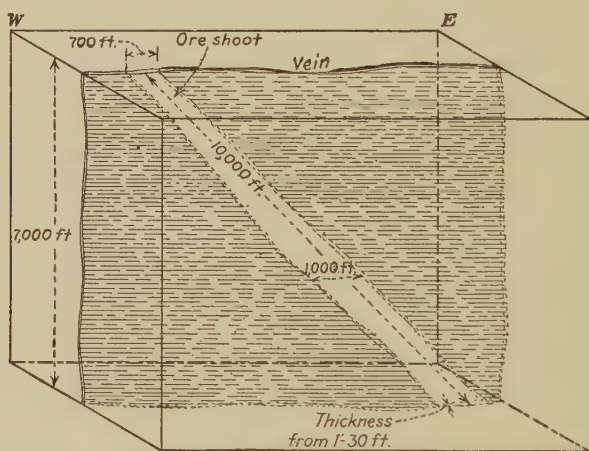


FIG. 110.—Stereogram of the ore shoot of the Morro Velho mine of the St. John del Rey Company, Brazil. Mining has extended (1928) down the shoot for 10,000 feet.

Morro Velho Mine.—The company developing the Morro Velho mine was organized in 1830, and at present (nearly 100 years later) the mine has reached a depth of about 7,000 feet. The ore body pitches about 45° along the vein (Fig. 110), and has been followed over 10,000 feet on the incline. At this depth, the deposit is about 1,000 feet long and 12.5 feet thick. The temperature in the mine at this depth is over 46°C . (115°F .), so the problem of creating a working temper-

ature is an important one. The ore consists of *native gold*, pyrrhotite, pyrite, chalcopyrite, arsenopyrite, quartz, and siderite. Its average value is about \$10 or \$11 worth of gold per ton.

KOLAR GOLDFIELD, INDIA

The Kolar goldfield is located in the eastern part of Mysore in southern India. The ores are found in the Champion Reef, a gold-quartz vein that cuts the pre-Cambrian metamorphic rocks. The reef strikes north and south and dips west about 50 or 55°. Its maximum thickness is 40 feet. The chief ore mineral is *native gold*, associated with pyrrhotite, chalcopyrite, pyrite, and arsenopyrite. One ore body has been followed downward for over 6,000 feet. The ore is of excellent grade, averaging from \$20 to \$25 worth of gold per ton.

OTHER IMPORTANT FOREIGN GOLD AND SILVER DEPOSITS

Our discussion of foreign gold and silver districts does not, by any means, exhaust the list of them. Other famous gold and silver mines are found in Russia and Sibe ia, Japan, Australia, Burma, Germany, and other countries.

USES OF GOLD AND SILVER

Gold is wealth and the whole of wealth. It is also the brilliant ornament *par excellence*, the untarnishable glitter of which recalls the sun; but above all it is the concrete image, the figurative reduction into a few discs of human fortune and all the enjoyments which fortune implies . . . To insist further upon this property of gold would be platitudinous. All that can be said has been said, and well said, of the yellow metal's power to embody and concentrate in the most convenient and palpable form the product and the apparent end of human labor, the synthesis of effort, which is destined the next moment to be dispersed in the satisfaction of desires, in enjoyments and pleasures, every one of which will still be expressible in terms of more or fewer of its particles. Gold has been cursed and blessed; it has been successively, sometimes childishly, deified and abhorred.¹

In order to reach some of the desired goals, so well stated by De Launay, every part of the world has been or is being searched for gold; once found it is feverishly dug from the ground and extracted for man's use. The uses of gold vary, and the amount that enters into each has varied from time to time. In 1908, De Launay estimated that 40 per cent of the world's gold was used for industrial and ornamental purposes; 44 per cent, for coins; and 16 per cent was exported to the East (the vortex into which much of the world's silver and some of the gold disappears). In 1927, \$32,857,491 worth of gold, or 72 per cent of the domestic production in the United States, was used in the arts and

¹ DE LAUNAY, "The World's Gold," pp. xvi, xvii, 1908.

manufactures; and an additional \$26,461,237 worth of secondary gold was also used for these purposes. The quantity of new silver used in the arts and manufactures in this country in 1927 was 28,493,290 ounces, which was 47 per cent of our silver production that year. A little over 10,000,000 ounces of secondary silver was also so used.

It is the physical properties of gold that make it so useful in the arts and manufactures. It is insoluble in the common acids but is readily soluble in aqua regia. It is extremely ductile and malleable. It is too soft to be used alone; hence is alloyed, usually with copper and silver. The purity of gold alloys is spoken of as "fineness" (already defined) or as "carats." A carat is 1 part gold in 24 parts; for example, 18 carat means 18 parts gold and 6 parts of some other metal or metals.

Use of Gold in Ornamentation.—The making of jewelry accounts for a large part of the gold consumed in the arts. In recent years, since platinum has become so popular, gold alloys that are white (half gold and half silver) and green (about 30 per cent gold and 70 per cent silver or an alloy of cadmium and gold) have been put on the market. Gold is used in dentistry; for gold plating; for decorating glass and chinaware; for gilding statuary, picture frames, and art objects of all kinds; on book bindings and the edges of the leaves; for gold lettering; and for interior decoration, as in churches and many other kinds of buildings. The cost of gilding is small because of the thinness of the gold leaf used.

Gold Leaf.—Gold leaf is made by beating the gold out by hand, as machines for rolling the metal have not been successful. The methods used 5,000 years ago are, therefore, still in use. In Pliny's time, gold leaf as thin as $1/70,000$ inch was made, but the commercial product today averages $1/200,000$ inch in thickness. Such a thin sheet permits the passage of light through it.

In making gold leaf, 200 sheets of gold, each 1 inch square and $1/800$ inch thick, are placed in a pile on a sheet of tough vellum 4 inches square. These sheets are hammered with a 16- or 18-pound hammer until those that were 1 inch square have become 4 inches square. These pieces are then cut into four pieces each, and the resulting 800 pieces are placed in a pile between sheets of goldbeater's skin. Goldbeater's skin is made from the large intestine of the ox, and the intestines of 500 oxen are necessary to form 900 finished skins. The total thickness of the 800 gold sheets and the skins is only about $3/4$ inch. These pieces are beaten and again quartered, forming 3,200 pieces, each 4.5 inches square. These pieces are put between skins and beaten until they are 5 inches square. These final sheets of gold are the present commercial gold leaf, $1/200,000$ inch thick. The 1 square inch of the original sheet has thus become 400 square inches (Fig. 111). An ounce of gold of this thickness will cover about 100 square feet of surface. The metal can be beaten even thinner, as a thickness of $1/367,500$ inch has been attained. One grain of gold

(worth \$0.043) of the last-mentioned thickness will cover 52 square inches of surface.

Gold (and Silver) Lace.—Another common use of gold (and silver, also) that depends upon its ductility is in making gold (and silver) lace. The gold threads are made by pressing gold leaf upon a silver rod and drawing the rod into a fine wire. The last drawing is through a die made by drilling a hole in a diamond or ruby. The gilded wire is wound over a silk thread, which is then made into lace and various fabrics. The gilded wire is so fine that an ounce of it is a mile and a quarter long. The gold on the gilded wire is so thin that an ounce of it will cover 100 miles of the wire. An ounce of pure gold can be drawn into a wire 50 miles long. Much of the gold used in making the gold lace is an alloy of copper and zinc, known as “dutch metal.” Silver can be drawn out into wire of

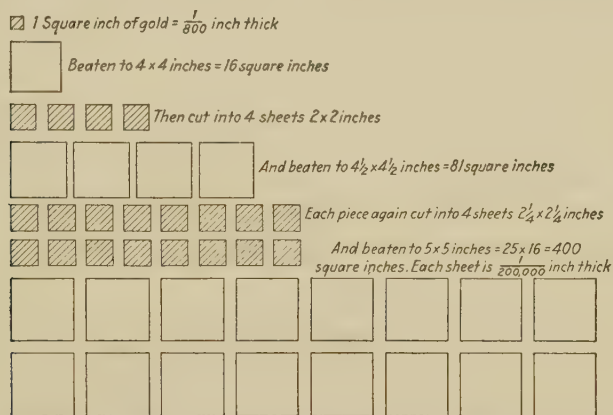


FIG. 111.—Diagram to show how 1 square inch of gold, $\frac{1}{800}$ inch thick, can be beaten into 16 pieces each $\frac{1}{200,000}$ inch thick, totaling 400 square inches. (Modified from *Lit. Digest*, Feb. 9, 1924, p. 24.)

the same size as the gilded wire and is then used in making silver lace and fabrics.

Use of Gold and Silver in Coinage.—Gold and silver are widely used for coins. The standard metal for gold coins in the United States is 9 parts gold and 1 part copper and for silver coins, 9 parts silver and 1 of copper. More copper is used in the coins of some other countries.

Uses of Silver.—The uses of silver are in a measure similar to those of gold. Solid or plated silverware is an important item of most households. Many artistic products are made of this metal, though it is less extensively used on pottery, chinaware, and for gilding than gold, because it tarnishes readily. Considerable experimental work has been done in an attempt to make a silver alloy that will not tarnish; but, although some fairly durable alloys have been produced, all blacken eventually. Sulfur contained in foods and in the air readily unites with silver to form the familiar black tarnish, which is really silver sulfide. Silver (usually in

the form of an alloy) is used in making various types of instruments. Alloys of silver and gold are common.

The malleability and ductility of silver make its uses somewhat the same as those of gold that are due to those properties. Silver forms many valuable and important chemical and medical compounds. One of its most important chemical uses is in photographic materials. No less than 8,000,000 ounces of silver is used annually in the United States by the photographic and chemical industries alone.

Large amounts of silver are annually sold in the Orient (principally in India and China). Approximately 45 per cent of the world's annual production of silver finds its way into India. In 1924 and 1925, 60 per cent of the world's silver production went to India and China, and 75 per cent during the first half of 1926. The silver rupee is the standard of value in India; silver jewelry is highly prized there; and much silver is simply hoarded. It was proposed in 1926 to adopt a gold standard in India, and the effect of this (if it is done) upon the silver market is awaited with much interest by silver producers. As 70 per cent of the world's production of silver is obtained as a by-product from refining base metals, the chief sufferers would be those comparatively few mining companies that produce silver alone.

PRODUCTION OF GOLD AND SILVER IN THE UNITED STATES

Production by States.—The production of gold and silver in the United States comes from 25 states and territories (Alaska and the Philippine Islands), but only 9 produced over \$1,000,000 worth of gold in 1928, and only 8 produced over 1,000,000 ounces of silver. The leading gold- and silver-producing states, in the order of their production, in 1928 are given in the lists below:

Gold	Silver
1. California.	1. Utah.
2. South Dakota.	2. Montana.
3. Alaska.	3. Idaho.
4. Colorado.	4. Arizona.
5. Utah.	5. Nevada.
6. Arizona.	6. Colorado.
7. Nevada.	7. California.
8. Philippine Islands.	8. Texas.
9. Montana.	9. New Mexico.

These lists show that only six states produce both gold and silver in large quantities, the others producing dominantly gold or silver. The gold and silver output for many years has come largely from this group of states and territories. Figure 112 shows the production of gold in the United States from 1845 to 1928 and of silver from 1880 to 1928.

Producing Mines.—The gold and silver produced in this country in 1927 came from 3,328 mines, of which 1,280 were placer mines and 2,048 were lode mines. The average number of mines producing each

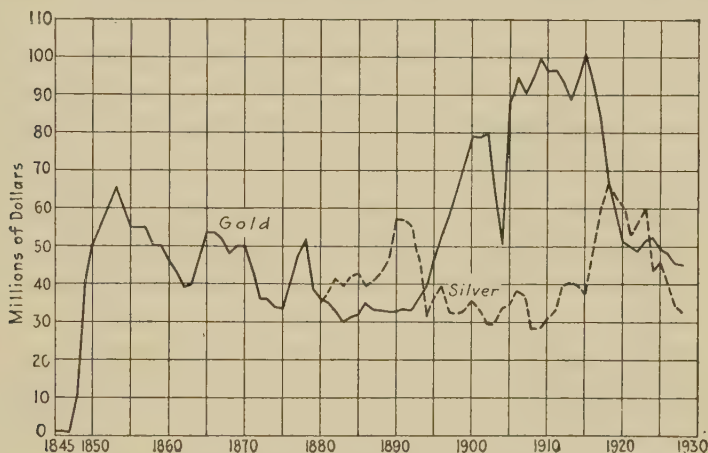


FIG. 112.—Curves showing the value of the gold production in the United States from 1845 to 1928 and of the silver production from 1880 to 1928. (Data from *U. S. Mineral Resources*.)

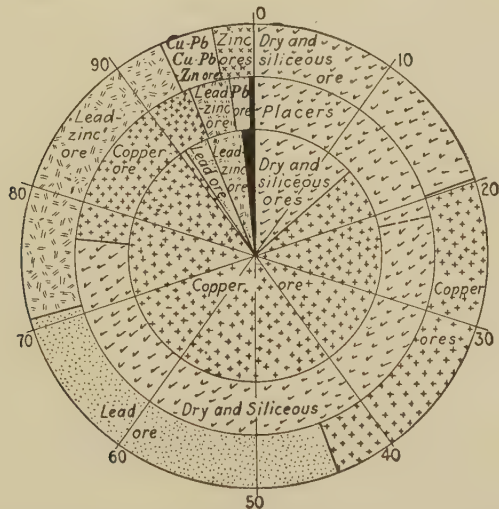


FIG. 113.—Sources of gold and silver (in 1927) by types of ore. Inner area is for gold and silver; middle circle, for gold; and outer circle for silver. Percentages are indicated by figures on the outer circle. (Data from *U. S. Mineral Resources*, 1927, Part 1.)

year for the last 10 years is 3,579, of which 1,243 were placer and 2,336 were lode mines. A comparison of these figures shows that the number of mines has remained about constant.

Production from the Various Types of Ores.—The production from gold and silver ores of various kinds is given in detail by the U. S. Bureau of Mines,¹ but for our purposes the graphic representation of this data in Fig. 113 will suffice. Of all the ores producing gold and silver in the United States in 1927, 77 per cent was copper ores (represented in inner area of figure), yet so low was the gold and silver content of these ores that they produced only 17.5 per cent of the gold production (represented in middle circle) and 24.4 per cent of the silver (represented in outer circle). On the other hand, though the dry and siliceous ores (placers included here) constituted only 13.25 per cent of the ores furnishing gold and silver (inner area of figure), they yielded 76.58 per cent of the gold production (middle circle) and 21.79 per cent of the silver (outer circle). The common association of lead and silver can also be seen from this figure; 54.64 per cent of the silver production in the United States in 1927 came from the various types of lead ores.

No less than 21.4 per cent of the gold production of the United States came from placers in 1927. During the 10-year period preceding 1927, 63 per cent of the gold production came from dry and siliceous ores; 23 per cent, from placers; 10 per cent, from copper ores; and 4 per cent, from all the other kinds. The largest increases in the production of silver have come from the complex copper-lead-zinc ores.

Total Production of Gold and Silver in the United States.—The following table gives the total production of gold and silver in the United States from 1792 to 1927. (It should be remembered that the weight of gold and silver is always given in troy ounces, also called "fine ounces." A troy ounce can be converted into avoirdupois by dividing by 1.097.)

TABLE 52.—PRODUCTION OF GOLD AND SILVER IN THE UNITED STATES, 1792-1927¹

Period	Gold		Silver	
	Fine ounces	Value	Fine ounces	Value
1792-1847	1,184,977	\$ 24,537,000	309,500	\$ 404,500
1848-1872	58,279,781	1,204,750,000	118,568,200	157,749,900
1873-1927	155,286,832	3,210,063,700	2,877,857,352	2,260,244,867
Total	214,753,590	4,439,350,700	2,996,735,052	2,418,399,267

¹ U. S. Bur. Mines, 1927.

Secondary Gold and Silver.—The recovery of used gold and silver, especially the former, is of much importance. In 1927, \$26,461,237 worth of old gold was produced in the United States from waste materials, chiefly from jewelry and dental waste. This amount was equivalent to

¹ U. S. Mineral Resources, 1927, Part 1, pp. 618-630.

58 per cent of the value of the domestic production of new gold that year. Of the total amount of gold, both new and old, used in 1927, the value of the secondary gold was 44.6 per cent. Undoubtedly, recovering secondary gold is a cheaper process than producing new gold.

The quantity of secondary silver produced in 1927 in the United States was much less than that of gold. According to the U. S. Bureau of Mines,¹ a little over 10,000,00 ounces of secondary silver was recovered in 1927, or about 16 per cent of the production of new silver. This secondary silver was largely derived from old silverware and photographic waste, though also from old jewelry, dental waste, and other materials. The silver recovered from photographic materials was obtained from solutions, films, and plates. The solutions generally contain less than $\frac{1}{2}$ ounce of silver per gallon, and a million feet of film contains about 800 ounces of silver.

WORLD PRODUCTION OF GOLD AND SILVER

It would be interesting to know how much gold and silver man has had in his possession since he first learned the use of the precious metals,

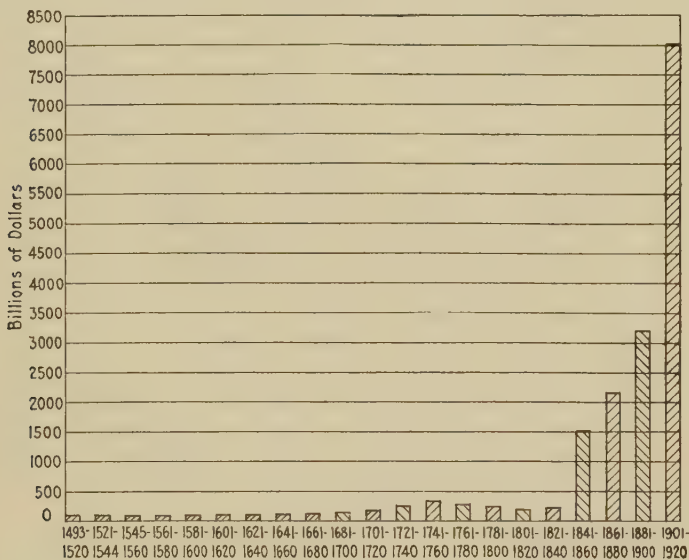


FIG. 114.—World production of gold from 1493 to 1920 by approximate 20-year periods. Value in dollars on a basis of \$20.67 per troy ounce. (Data from many sources.)

but no basis exists for estimating these amounts, to say nothing of possible figures. The first figures of total world production that are available, strange as it may seem, date back only to 1493. Placing the modern value (\$20.67 per troy ounce) of gold on the estimated production of the earlier periods, the total value of the gold production of the world from

¹ U. S. Mineral Resources, 1927, Part 1, p. 600.

1493 to the end of 1927 would be \$30,588,172,700.¹ The world's total production of gold by periods is shown in Fig. 114. The total production of silver from 1493 to 1927 was 447,238,999 kilograms, or 491,962.8 tons avoirdupois.

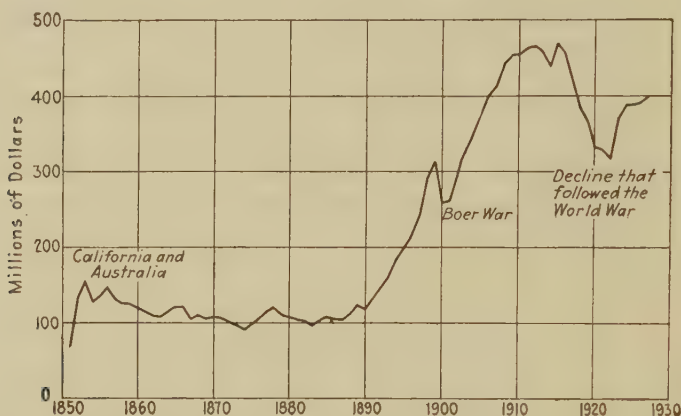


FIG. 115.—Curve showing the world's annual production of gold from 1851 to 1928. (*Mineral Industry.*)

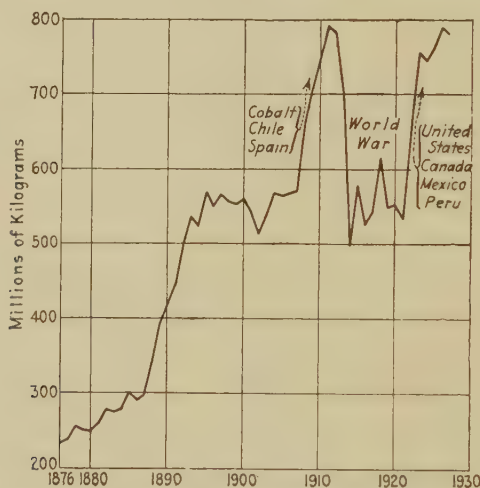


FIG. 116.—World production of silver, in kilograms, from 1876 to 1927. 1 kilogram = 32.15 troy ounces. (*Mineral Industry.*)

The value of the world's production of gold in 1927 was \$400,988,000, which is not far from that of the annual average world production during the last 25 years. The Rand goldfield in South Africa produced over 57 per cent of the world's gold in 1927 (\$228,870,000 worth); the United

¹ This is a much higher value than is placed by some authors on the total gold production. One figure given in 1920 (Spurr, "Political and Commercial Geology" p. 463) was \$9,000,000,000.

States was second, with \$45,418,000 worth, or a little over 11 per cent; and Canada was third, with \$38,130,000 worth, or 9.5 per cent. Other producers in 1927 were (value of production in round numbers) Russia and Siberia, \$22,000,000; Mexico, \$15,000,000; Australia, \$13,000,000; India, \$8,000,000; and Japan \$6,000,000. The world's production of gold from 1851 to 1928 is shown in Fig. 115.

The world's production of silver in 1927 was 251,108,300 ounces, of which North America was responsible for 190,775,400 ounces, or 76 per cent of the total. The four leading countries, in order of production, that year were Mexico, United States, Canada, and Peru. Together, these countries produced 205,916,800 ounces of silver, or 82 per cent of the world's output. Australia, Burma, Germany, Bolivia, Japan, Central America, and Spain followed next in order. The world's production of silver from 1876 to 1927 is shown in Fig. 116.

SELECTED READINGS ON GOLD AND SILVER

There is a large amount of literature on gold and silver from which the following references have been selected as representative.

CONNOLLY and O'HARRA: *The Mineral Wealth of the Black Hills, S. Dak. School Mines Bull.* 16, 1929.

DE LAUNAY, LOUIS: "The World's Gold," G. P. Putnam's Sons, New York, 1908.

EMMONS, W. H.: "The Principles of Economic Geology," pp. 401-473, McGraw-Hill Book Company, Inc., New York, 1918.

LEITH, C. K.: "Economic Aspects of Geology," pp. 221-237, Henry Holt & Company, 1921.

LINDGREN, WALDEMAR: "Mineral Deposits," McGraw-Hill Book Company, Inc., New York, 1928. Contains much excellent material.

MEADE, E. S.: "The Story of Gold," D. Appleton & Company, 1919.

ORCHARD, J. E.: Gold, Spurr's "Political and Commercial Geology," pp. 462-494, McGraw-Hill Book Company, Inc., New York, 1920.

PAINE, F. W.: Silver, *idem*, pp. 495-505, McGraw-Hill Book Company, Inc., New York, 1920.

RASTALL, R. H.: "The Geology of the Metalliferous Deposits," pp. 454-497, Cambridge University Press, 1923.

RIES, H.: "Economic Geology," pp. 658-749, John Wiley & Sons, Inc., 1925. Contains a splendid bibliography.

U. S. Mineral Resources and *Mineral Industry* contain much material on gold and silver.

The U. S. Geological Survey has issued a series of excellent reports upon the various gold and silver deposits in the United States. A few of these relating to some of the more important districts are given below, and others may be found in the bibliographies issued by the U. S. Geological Survey. For convenience in finding a special report, they are listed by the locality titles.

Alaska Juneau Mine: A. C. Spencer, *U. S. Geol. Survey Bull.* 287, pp. 1-137, 1906.

Cripple Creek, Colorado: Lindgren and Ransome, *U. S. Geol. Survey Prof. Paper* 54, 1906.

Georgetown Quadrangle, Colorado: Spurr, Garrey, and Ball, *U. S. Geol. Survey Prof. Paper* 63, 1908.

Goldfield, Nevada: Ransome, Emmons, and Garrey, *U. S. Geol. Survey Prof. Paper* 66, 1909.

- Jarbridge District, Nevada: F. C. Schrader, U. S. Geol. Survey *Bull.* 471, 1923.
- Park City, Utah: J. M. Boutwell, U. S. Geol. Survey *Prof. Paper* 77, 1912.
- San Juan Area, Colorado: J. E. Spurr, U. S. Geol. Survey *Prof. Paper* 63, pp. 111-118, 1908.
- Tertiary Gravels of the Sierra Nevada of California: Waldemar Lindgren, U. S. Geol. Survey *Prof. Paper* 73, 1911.
- Tintic District, Utah: Lindgren and Loughlin, U. S., Geol. Survey *Prof. Paper* 107, 1919.
- Tonopah, Nevada: J. E. Spurr, U. S. Geol. Survey *Prof. Paper* 42, 1905.
- Tonopah, Nevada: Bastin and Laney, U. S. Geol. Survey *Prof. Paper* 104, 1918.

CHAPTER IX

TIN

Man has long possessed a knowledge of tin and its uses. The bronze (an alloy of copper and tin) age, as we have seen, followed the copper age, though as to the extent of ancient man's metallurgical knowledge we have the most meager evidence. Tin has continued to be used all down through the ages, and its yearly world production today (1928) is greater than at any previous time in its history. In the United States, the use of only iron and copper exceeds in value the use of tin. The United States produces less than \$50,000 worth of tin annually yet is the largest consumer of tin in the world. The rank of this metal is shown in the following table, which gives the value of the amount of each of the eight leading metals used in the United States in 1928:

TABLE 53.—VALUE OF THE AMOUNT OF THE EIGHT LEADING METALS USED IN THE UNITED STATES, 1928¹

Metal	Value
Iron (pig).....	\$661,351,270
Copper.....	262,930,000
Tin (imports).....	86,983,000
Lead.....	72,639,000
Zinc.....	72,166,000
Aluminum.....	47,899,000
Gold.....	45,360,000
Silver.....	32,772,000

¹ *U. S. Mineral Resources, 1928.*

Abundance of Tin.—The amount of tin in the outer part of the earth's crust, as estimated by Clarke and Washington, is 0.000, X per cent; as estimated by Berg, 0.0005 per cent. Tin ranks as the thirty-eighth element in abundance in the outer part of the earth's crust. Its rank in this is close to those of arsenic and molybdenum.

Physical Properties of Tin.—Tin is a white metal and is soft, malleable, and ductile. It can be rolled into thin sheets (foil) or drawn into fine wires. It melts at 228°C. It has a fibrous crystalline structure and when bent emits a crackling sound ("tin-cry"). This sound is due to friction as the fibrous crystals glide over one another. If the tin is bent rapidly and repeatedly, considerable heat is developed. Tin is very resistant to many acids and is not acted upon by air; hence its extensive use in coating (tinning) other metals, especially iron. Tin forms numer-

ous alloys the chief of which are with copper, lead, zinc, antimony, and bismuth.

Mineralogy of Tin.—The chief source of tin is the oxide *cassiterite*, SnO_2 . Another tin mineral is *stannite*, $\text{Cu}_2\text{FeSnS}_4$; but it is of little importance as a source of tin, being mined only in certain silver-tin deposits in Bolivia.

Physical Properties of Cassiterite.—Cassiterite is hard, its hardness being 6 to 7; and it is heavy, its specific gravity being 6.8 to 7.1. It is relatively insoluble in the ordinary weathering solutions. It is generally brown or black but may be lighter.

Gangue Minerals in Tin Deposits.—Quartz is the most common gangue mineral in tin ores. It is usually accompanied by a number of high-temperature minerals, chiefly arsenopyrite, wolframite, molybdenite, fluorite, topaz, tourmaline, and apatite. In many deposits of tin, the chief gangue minerals are quartz and muscovite.

Mode of Occurrence of Tin Ores.—Cassiterite is a persistent mineral, though it is especially characteristic of the high-temperature veins. Disseminated deposits of it occur in the intensely altered wall rock along the veins or lodes. The major part of the world's tin comes from high-temperature veins or, rather, from the placers which are derived from them by weathering. The amount of cassiterite in placers ranges from $\frac{1}{2}$ pound (as in the Malayan deposits) to 20 or 30 pounds per cubic yard. Cassiterite, in limited amounts, occurs in pegmatites, in contact-metamorphic deposits, and in the intermediate vein zone.

Origin of Tin Deposits.—All tin deposits are of magmatic origin, which is shown by their mineralogy, association with igneous rocks, and the intense alteration that the associated rocks have undergone. The hot solutions forming the deposits must have contained strong gases and acids and been under considerable pressure. The exact method by which the tin is transported is not fully understood, but the evidence indicates that as gaseous tin chloride or fluoride, it was transported with the other gaseous constituents of the magmas. The tin chlorides and fluorides exist as gases under the high temperatures prevalent in the deep-seated vein zone. The reaction of these compounds with water vapor would give rise to cassiterite; and the acids HCl and HF would be liberated. These strong acids attacked the feldspar of the wall rocks and converted it into muscovite and quartz, forming a rock called "greisen." Fluorite and topaz (two fluorine-bearing minerals) are of common occurrence in tin ores, which is further evidence that this line of reasoning is correct.

TIN DEPOSITS OF THE UNITED STATES

There are no important deposits of cassiterite in the United States, although there are many small occurrences of it. Such small deposits

are found in the York district, Seward Peninsula, and other points in Alaska; in Lander County, Nevada; the Black Hills, South Dakota; Lincoln County, North Carolina; Gaffney, Cherokee County, South Carolina; and the El Paso Mountains (north of El Paso), Texas. A few tons of tin have been produced in these localities.

FOREIGN TIN DEPOSITS

The world's supply of tin comes from widely scattered areas, as the map of Fig. 117 reveals. The greatest tin area in the world begins on the islands of Billiton and Banka in the Dutch East Indies, extends through the Federated Malay States and Siam, and on into Burma, India. Farther to the north, in the province of Yunnan, China, other deposits occur. Important tin deposits are also found in Bolivia, Nigeria, England (Cornwall), India, Australia, and South Africa.

The Deposits of the Malay States.—The Malay States led the world in the production of tin in 1928. Essentially all their tin comes from alluvial gravels. The original lodes are dominantly quartz veins in sedimentary, metamorphic, and igneous rocks. These rocks are cut by intrusive granites. The deposits are of low grade, and the mining methods in the past have been crude and wasteful, but dredges are now being introduced, which will greatly improve the productivity of the district. The 1928 production of almost 65,000 tons was the largest on record.

Deposits of Billiton and Banka Islands, Siam, and Burma.—The Dutch islands of Billiton and Banka were second in importance in this great tin belt in 1928. The tin comes from gravels, which originated from veins similar to those of the Malay deposits. The deposits of Siam and Burma resemble those of the other two producing areas of this belt.

Tin Deposits of Bolivia.—The Bolivian tin deposits are second in world production and are the largest tin lode deposits in the world. A small production is made from placers. The tin deposits are scattered over a considerable area to the south of La Paz.

The ore occurs as veins that cut igneous and sedimentary rocks (mainly sandstones and quartzites). The veins are well defined, and some are 5 feet in width. The ores consist dominantly of pyrite, with cassiterite as next in abundance. A number of other minerals are present, some of which are silver bearing. The rare tin mineral stannite occurs in the district. Some of the ore contains as high as 8 per cent tin. The richness of the ores and the unusual minerals associated with them place these deposits among the remarkable tin reserves of the world.

Tin Deposits of Nigeria.—Although the tin deposits of northern Nigeria have been worked only since 1909, they are an important source of tin. The primary rocks of the region are ancient gneisses and schists which are cut by granites and granite porphyry. Tin veins occur in

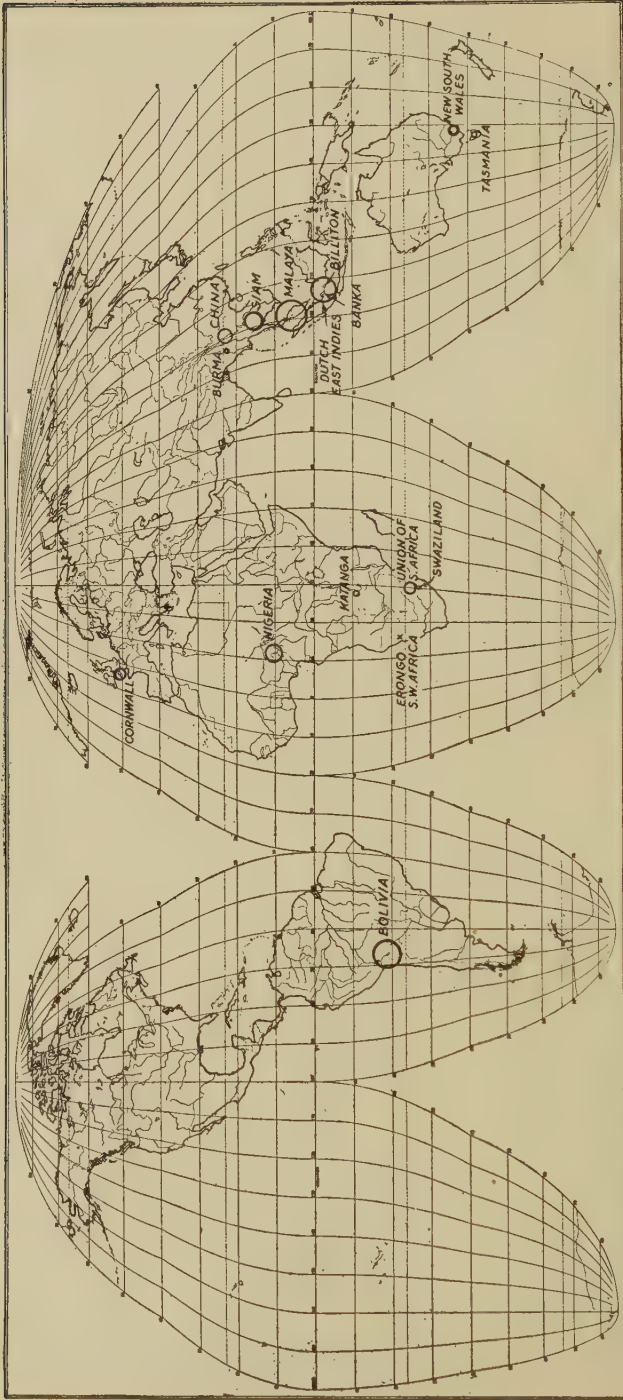


Fig. 117.—The important tin-producing areas of the world. (Modified after Knopf, *U. S. Mineral Resources*, 1917, Part 1, pl. 1, p. 70.)

all types of rocks, but none of them is mined at present (1928). The production comes from gravels resulting from the deep weathering of the ancient rocks. The tin concentrates are of a very high grade, averaging 70 per cent metallic tin.

Australian Tin Deposits.—The Australian tin deposits are in New South Wales, Queensland, Northern Territory, and Tasmania. Both lode mines and placers are sources of the tin. The most important deposits are in Queensland and Tasmania. The production from the whole of Australia in 1927 was only 2,620 tons.

The Tin Deposits of Cornwall, England.—The famous Cornwall tin deposits have been known and worked since before the time of the Romans; in fact, there is some evidence that they were worked by the Phoenicians, 1000 B.C. The deposits are well-defined fissure veins, that cut both the intrusive granite and the slates or "killas." The veins dip steeply and range from 1 foot to 50 feet in width. The mineralogy of the ores is variable. Cassiterite and quartz are the chief minerals in the deposits; but wolframite, fluorite, topaz, arsenopyrite, and numerous other minerals occur, also. Not all these minerals are found associated in one mine. Some parts of the ores contain much tourmaline, and other parts are chloritized. The ores vary much in value but, as a whole, are of low grade. Few contain more than 30 pounds of cassiterite per ton. An interesting feature of these deposits is that the tin ores grade into a copper zone which, in turn, becomes a lead-zinc zone that grades into an outer iron zone. Davison has shown, in his valuable papers on the district, that this zonal arrangement holds throughout the area.

USES OF TIN

To say that tin has few uses that are essential seems paradoxical when we recall that it is third in use among all metals in the United States. Approximately 87 per cent of the tin utilized in this country goes into tin and terne plate, solder, babbitt metal, bronze, and brass. The most essential of its uses is in the manufacture of containers for foods, yet it is not an absolute necessity for this purpose, as glass and earthenware containers can be used. In fact, the housewife who cans her own fruits and vegetables uses glass containers almost to the exclusion of those made of tin. Furthermore, since absolutely pure aluminum can now be produced (insuring safety in its use), its substitution for tin in food containers is feasible; and, what is very important, the secondary recovery of aluminum is possible, whereas very little of the tin used on containers is ever recovered.

The amount of tin employed for each of its various uses in the United States in 1925 is given in the following table:

TABLE 54.—TIN CONSUMPTION BY USES IN THE UNITED STATES, 1925¹

Use	Tons
Tin and terne plate.....	34,481
Solder.....	28,406
Babbitt metal.....	22,365
Bronze and brass.....	16,749
Foil.....	2,993
Collapsible tubes.....	2,473
Chemicals.....	2,152
Tinning sheets, plates, and tubes.....	1,946
Castings.....	1,063
White metal.....	1,041
Type metal.....	909
Tinning wire, nails, and other objects.....	695
Miscellaneous ²	2,133
Total.....	117,406

¹ FURNESS, J. W., *Mineral Industry*, 1926, p. 658.² Included in miscellaneous uses are soda-fountain supplies, britannia metal (Sn, Cu, Sb), bell metal (Sn, Cu), fire sprinklers (fusible alloys used), and the preparation of silk.

Use in Tin and Terne Plate.—The manufacture of tin plate and terne plate is influenced by the demand for containers. In 1927, there was a decrease of over 100,000 tons in the manufacture of tin plate in the United States, which meant a decrease of about 2,000 tons in the amount of tin used. In spite of fluctuations, however, the use of tin in making tin plate is the dominant one. Tin plate is made by covering sheet iron or mild steel with a thin coating of tin either by dipping or spraying. Terne plate is a cheaper grade of tin plate made by using a coating of tin and lead instead of pure tin. According to J. W. Furness of the U. S. Bureau of Mines, 60 per cent of the tin used in tin and terne plate goes into tin cans or other tin containers. At the close of the Civil War, approximately 5,000,000 cans were used annually in the United States, and 60 years later, in 1925, over 8,300,000,000 cans were used. The possibility of using food containers coated with organic lacquers offers, according to Furness, an interesting field for research. Containers having such coatings are now being used for certain foods.

Use in Solders.—The second most important use of tin is in making solders, especially the "soft" solders, so-called because they fuse at low temperatures. Solders vary in composition, but the most widely used soft solder before the World War contained 50 per cent tin and 50 per cent lead. During the war, it was found that 40 per cent tin and 60 per cent lead produced a solder that was fully as satisfactory as the other. The major uses of solder are in the manufacture of food containers, automobile radiators, and electrical materials. Solders containing as low as 35 per cent tin can be used in radiators; in making cans, a solder containing about 37.5 per cent tin is required. Too little tin raises the melting point of the alloy. The addition of bismuth lowers the melting point, producing the very fusible alloys. The addition of 1 pound of

cadmium would displace 3 to 5 pounds of tin in solders, and it would be possible to use up to 30 per cent cadmium. If cadmium were thus substituted, it would mean a saving of 80 per cent of the tin now used in solder. The adoption in recent years of the so-called "sanitary" or "open-top" type of can will reduce the use of solder. The cover of this can is double seamed and is pressed on with a gasket. Practically all food products save meat and milk can be placed in such containers. Another substitute for tin solder is "amaloy," said to contain 98.5 per cent lead and 1.5 per cent phosphorus and tin. It can be used for practically the same purposes as normal solder.

Use in Babbitt Metal.—Babbitt metal has a variable content of tin and other metals. The original alloy as invented by Isaac Babbitt consists of 24 parts tin, 8 parts antimony, and 4 parts copper. This mixture is a good, hard bearing metal. The proportions of the metals in the alloy now vary, however. Furness describes one babbitt metal that consists of 89 parts tin and 11 parts lead. Antimony and copper are substituted for lead to make a hard bearing metal. Much larger amounts of lead could be substituted for tin, and except for high-speed bearings the product would be just as satisfactory. Roller and ball bearings are replacing bearings made of babbitt metal.

Use in Bronze.—Bronze contains variable amounts of tin and copper. There are numerous varieties of bronze alloys on the market, but there is no fixed agreement as to the composition of materials of the same name. Gun bronzes contain from 9 to 11 per cent tin and the remainder copper. Bell metal contains from 18 to 30 per cent tin, the remainder copper. Speculum metal has 33 per cent tin and 67 per cent copper. A very tough bronze, known as "phosphor" bronze, contains 89 per cent copper, 10 per cent tin, and 1 per cent phosphorus.

Other Uses of Tin.—Tin has numerous other uses. In making foil and collapsible tubes, aluminum can be substituted for it. It has been estimated that 1,000 tons of tin is used annually in treating silk to make it rustle and add weight to it. Tin so used is wasted. It is of interest to note that tin has largely replaced mercury in making mirrors.

PRODUCTION OF TIN IN THE UNITED STATES

The production of primary tin in the United States is insignificant, the total in 1928 being 46 tons and the total for the last 10 years only 187 tons. In spite of this lack of important tin deposits, the United States, which depends upon other nations for markets for *its* surplus metals and, moreover, requires enormous quantities of tin, has in the tariff act of 1922 a provision for a 4-cent duty on tin ore and a 6-cent duty on tin to be levied as soon as the annual domestic production reaches the astounding figure of 1,500 tons, or a trifle more than 1 per cent of our needs.

Selected Readings on Tin

- FURNESS, J. W.: Tin, *U. S. Mineral Resources*, 1925, Part 1, pp. 65-88; 1927, Part 1, pp. 119-155.
- HILL, J. M.: Spurr's "Political and Commercial Geology," pp. 317-336, McGraw Hill Book Company, Inc., 1920.
- KNOFF, ADOLPH: Tin, *U. S. Mineral Resources*, 1917, Part 1, pp. 63-72. Contains map of world and bibliography.
- LINDGREN, WALDEMAR: "Mineral Deposits," pp. 725-744, McGraw-Hill Book Company, Inc., New York, 1928.
- RASTALL, R. H.: "Geology of Metalliferous Deposits," pp. 260-280, Cambridge University Press, 1923.

CHAPTER X

ALUMINUM

The extensive use of aluminum by man is of recent date, as a commercial metallurgical process for extracting it was not perfected until 1855. In that year, aluminum was selling for \$90; in 1890 it sold for \$1; and at present (1928) it sells for about \$0.25 a pound. The United States produced 61,281 pounds of aluminum in 1890; 7,150,000 pounds in 1900; and over 136,000,000 pounds in 1927. Aluminum smelters require an abundance of electrical energy, so the plants in the United States are located at Niagara Falls and other places where, by the use of water power, electricity can be produced cheaply.

Abundance of Aluminum.—Aluminum is the third element in abundance in the outer part of the earth's crust; the percentage amount, as given by Clarke and Washington, is 8.07. It is the most abundant metal in the earth's crust, and yet the element was not isolated until in 1828, by Wohler.

Physical Properties of Aluminum.—Aluminum is tin-white. It possesses great tensile strength, from 15,000 to 20,000 pounds per square inch, or about that of cast iron. It is very ductile and malleable but hardens (like gold and silver) while it is being worked and has to be annealed frequently. It can be drawn into wires that are from 0.0005 to 0.0001 inch in diameter, and it can be rolled into very thin sheets. The electrical conductivity of aluminum is 50 (copper 90 and silver 100), and its thermal conductivity is 38 (copper 73.6 and silver 100). It does not tarnish easily but retains a polished surface a long time.

Mineralogy of Aluminum.—The chief ore of aluminum is *bauxite* (pronounced "bō'zīt"), a mixture of hydrated aluminum oxides. The composition of this ore is variable, the actual ore containing from 52 to 60 per cent Al_2O_3 . Other hydrated oxides of aluminum are known, but they are unimportant as a source of aluminum. One of these minerals, *diaspore*, is used in making refractories. Aluminum is present in numerous silicate minerals, such as the feldspars and kaolin, but a successful commercial method of extracting it from such minerals has not yet been developed.

Physical Properties of Bauxite.—Bauxite exists as amorphous earthy masses or as rounded concretionary particles (Fig. 118), that range from $\frac{1}{4}$ to 1 inch in diameter. This pisolitic structure is typical of many

bauxite ores. Bauxite is commonly colored yellow or red by iron oxides, but when pure it is white. It varies in hardness but is usually soft.

Mode of Occurrence of Bauxite.—Bauxite occurs as residual deposits at or near the surface and as lenses in sediments. Bedded deposits of it are usually associated with unconformities. A few reserves occur as pockets in limestones and sandstones. The major production comes from residual deposits. Bauxite ores are relatively thin bodies; in most districts they are less than 10 feet thick. In Arkansas, they average about 11 feet. The ore bed at Baux (the village from which bauxite

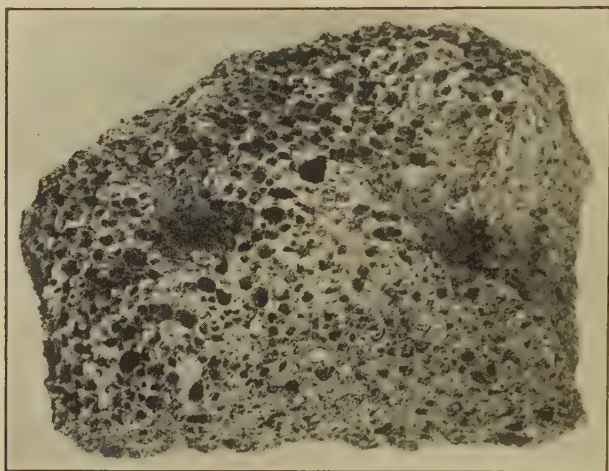


FIG. 118.—Bauxite from Arkansas. Two-thirds actual size. (Photograph by J. F. Barham.)

gets its name), province of Bouches-du-Rhône, France, is about 30 feet thick.

Origin of Bauxite.—The origin of bauxite has been explained in several ways, but the most common and generally accepted theory is that it represents the end product in the chemical decay of an aluminous silicate mineral. Under this theory, the ores are often spoken of as “lateritic” ores, but the term should be restricted to residual deposits consisting dominantly of iron. The most outstanding illustration in the United States of residual bauxite ores is the bauxite deposits of Arkansas. Mead has clearly proved that the original rock was a syenite the feldspar of which was altered to kaolin, which, as chemical weathering continued, was also broken up. The silica of the kaolin was carried away and the hydrated Al_2O_3 (bauxite) left behind. Any iron and titanium present in the original rock are now in the aluminum ore. Wherever bauxite deposits are fairly extensive and lie at essentially the same elevation and especially if there is an unconformity associated with the ores, the evidence is strong for their being residual deposits, like those of Arkansas. The

bauxite deposits of France, Alabama, Georgia, and probably Tennessee are certainly residual, although some men have advocated different theories for both the Alabama and Georgia deposits.

Hayes advanced the theory that the Alabama bauxite was precipitated from rising solutions which had obtained the aluminum by breaking up kaolin below. The source he proposes for the solutions is very inadequate, and the deposits can more easily be explained by regarding them as the result of leaching. Shearer has accounted for the pockets of bauxite associated with the kaolin deposits of Georgia as follows: sulfide solutions entered the bottom of the lake in which the kaolin was being deposited and were oxidized to sulfuric acid which broke up the kaolin and formed the aluminum hydrate or bauxite. Shearer's hypothesis is interesting, but its chief weakness is in the proposed source of the sulfide solutions. There are, apparently, conditions under which aluminum can be transported in solution and deposited, but large deposits have not commonly been formed in that way.

BAUXITE DEPOSITS OF THE UNITED STATES

The deposits of bauxite in the United States, in the order of their importance, are located in Arkansas, Georgia, Alabama, and Tennessee. Their location is shown on the map of Fig. 119.

Arkansas Deposits.—The Arkansas bauxite deposits are by far the most important in the United States. They occur in Pulaski and Saline counties in the east-central part of the state. The deposit of Pulaski County is a few miles south of Little Rock, and the one of Saline County is 18 miles southwest.

The bauxite beds rest on beds of clay beneath which is a syenite (Fig. 120). Above the bauxite are Tertiary sands, clays, and lignites. The syenite was weathered in pre-Tertiary times. The feldspar altered to kaolin which, in turn, was altered to bauxite. The entire alteration occurred in place, for some of the bauxite preserves the texture of the original syenite. Mead thinks that some of the aluminum oxide was carried downward and formed the pisolitic bauxite. He bases his opinion on the higher silica content of the ore at the surface, but the author of this text would suggest that it was the silica that was carried upward by capillarity and deposited at the surface, after the manner of the formation of caliche in the southwestern part of the United States. As the Tertiary seas advanced over this area, some of the bauxite was eroded and carried out into the water around the island of syenite rocks and was deposited with the clays, but most of it was untouched by erosion and was buried by Tertiary sediments. Subsequent erosion has reexposed the deposits.

The Saline County bauxite bed has a maximum thickness of 35 feet but averages only 11.5 feet. Most of the production comes from this

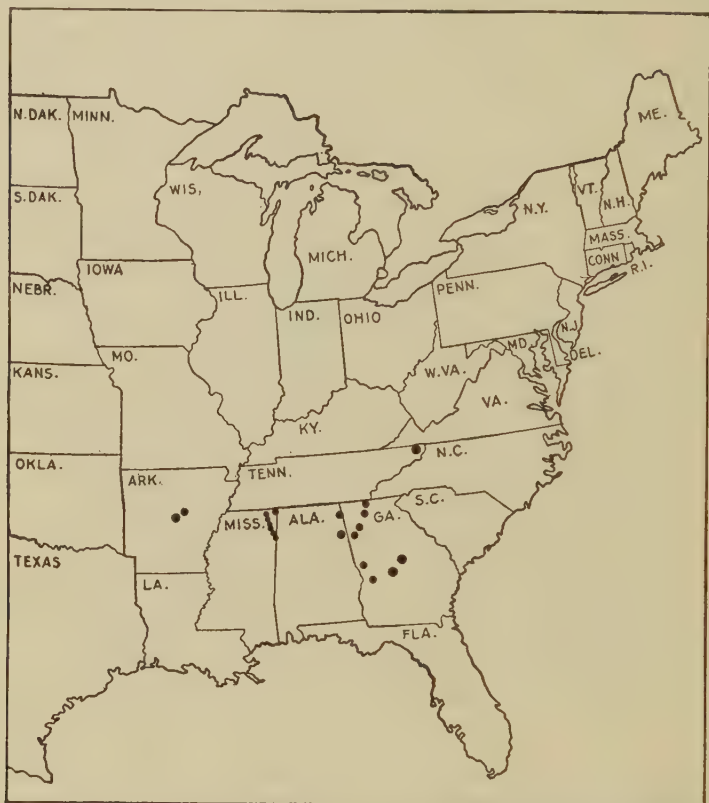


FIG. 119.—Map showing the location of the bauxite deposits of the United States. (U. S. Mineral Resources and other sources.)

county (1928). Some bauxite is recovered by stripping, and some by mining. The Pulaski County deposits are being actively developed and will be worked by mining.

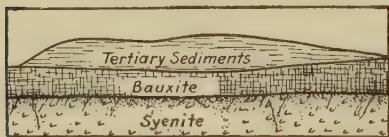


FIG. 120.—Ideal section of the Arkansas bauxite deposits showing bauxite on syenite, and kaolin (stippled area) as the intermediate stage between them. The bed is about 15 feet thick. (Sketch based partly on data from Mead, *Economic Geology*, vol. X, pl. 2, p. 28, 1915.)

are in Lower Cretaceous beds. The best deposits are those of the Cretaceous formation. The bauxite occurs as lenses in kaolin in both

Other Bauxite Deposits.—The bauxite deposits of Georgia are found largely in Wilkinson County and, to a lesser extent, in Twiggs, Washington, Baldwin, Macon, and Schley counties. The deposits in Macon and Schley counties are in Eocene strata, and those of all the other counties

formations, and in both there is usually an unconformity over the deposits. The ore grades into the kaolin. A bauxite bed rarely attains a thickness of 10 feet.

The deposits in *Alabama* and *Tennessee* also occur in association with clays.

FOREIGN BAUXITE DEPOSITS

Several foreign countries have enormous reserves of bauxite. Newly discovered deposits in the Atlas Mountains of *French Morocco* are estimated to contain 20,000,000 tons of ore in the top of the deposits alone. The bauxite reserves of *British* and *Dutch Guiana* are extensive, and large tonnages are exported from them annually. Those of *France* have been important producers for years, and that country led the world in the production of bauxite in 1927. *Hungary* has an estimated reserve of 200,000,000 metric tons of bauxite in the Northern Vértes Mountains and the Bakony Mountains on Lake Balaton. Other important deposits are in *Germany*, *Poland*, *Jugoslavia*, and *India*.

USES OF BAUXITE AND ALUMINUM

Uses of Bauxite.—The bauxite mined in the United States in 1927 was utilized as follows:¹ for manufacturing aluminum, 186,490 long tons; abrasives, 71,790 long tons; chemicals, 62,410 long tons; refractories, 160 long tons; and alumina cement, 90 long tons.

In Making Refractories.—Although alumina is an excellent refractory (pure Al_2O_3 melts at $2,050^\circ\text{C}.$), very little bauxite is used for this purpose. In 1927, only 160 long tons of bauxite was used as refractory material in the United States, but 40,085 tons of diaspore clay was so used (see *Refractories*, p. 626).

In Making Cements.—A high-alumina cement is made from bauxite, but only a little domestic ore was used for this purpose in 1927. It is estimated that 23,000 tons of Dalmatian bauxite was imported for this purpose that year. The cement is made by fusing bauxite and limestone in a small blast furnace. The product formed is ground and is then ready for use. It contains about 40 per cent lime, 40 per cent alumina, and 15 per cent iron oxides; and the other 5 per cent represents silica, magnesia, and loss on ignition. Such a cement will attain its full strength in 24 hours, whereas normal Portland cement requires 28 days. One of these rapid-setting cements is known as "lumnite" cement.

In Making Abrasives.—The abrasive industry consumed nearly 20 per cent of the domestic production of bauxite in the United States in 1927. In making abrasives, the bauxite is fused in an electric-arc furnace, and the alumina (Al_2O_3) allowed to crystallize. The crystalline material is crushed; sized; a bonding material is added; and the substance is then

¹ U. S. Bur. Mines.

molded into abrasive stones and wheels. The abrasive material has a hardness of 9, the same as corundum. This material is called "alundum" by one company. This fused material can also be used as a refractory and as a filtering device.

Chemical Uses.—The chemical industry requires a large tonnage of pure bauxite for the manufacture of aluminum salts, such as alum, aluminum chloride, aluminum sulfate, and alumina. A total of 137,870 long tons of bauxite was used for chemical purposes in the United States in 1927.

Production of Aluminum from Bauxite.—The manufacture of aluminum from bauxite is a difficult process, and the aluminum produced in the ordinary electric furnace is only 98 to 99 per cent pure. By recently developed electrolytic methods, aluminum that is 99.97 per cent pure is now produced. The raw materials used in an aluminum plant and the final products are shown in Fig. 121.

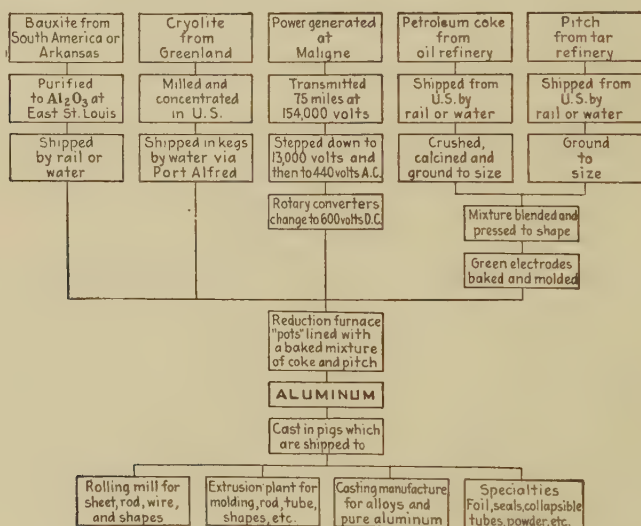


FIG. 121.—The sequence of events in the production of aluminum from the raw materials to the finished product at the plant of the Aluminum Company Ltd., Arvida, Canada. (After *Mineral Industry*, p. 20, 1926.)

Uses of Aluminum.—The uses of aluminum are as varied as those of iron or copper. The greatest field of usefulness of aluminum may be, like iron, in alloys; at any rate a vast number of aluminum alloys are made. Especially is the metal alloyed with copper and magnesium. The physical properties, durability, and the chemical inertness of aluminum make it adaptable to many uses. It may be drawn, rolled, pressed, or stamped into any desired form, or it may be cast; so aluminum sheets, rods, wire, tubes, and castings are being made.

Use in the Automobile Industry.—The automobile business consumes more aluminum than any other industry. No less than 40 pounds of aluminum was used in each of the 4,174,000 cars built in the United States in 1925, and increasing amounts have been so consumed in subsequent years. In 1928, it is estimated that over 20,000,000 pounds of aluminum pistons was used in this country as new equipment or replacements in automobiles. The United States is still far behind Europe in the use of aluminum in making automobiles, and it has been said that if as much aluminum was so used here as abroad, the automobile industry would consume the entire world production of this metal.

Use of Aluminum in the Manufacture of Other Vehicles.—There has been an important development in the use of aluminum and its alloys in making street and railway cars. Such cars not only require less power to haul but also are easier on the roadbeds. The reduction in weight on a standard street car amounts to 13,000 pounds, and the car requires 25 per cent less power to operate. The use of aluminum and its alloys in aircraft construction has made great advances in recent years. The need for minimum weight and maximum strength in such construction is self-evident.

Use of Aluminum in Making Household Products.—A very important use of aluminum is in the manufacture of household products. Over \$30,000,000 worth of such products was made in the United States in 1925. They include cooking wares and household appliances of all kinds. The use of aluminum as cooking ware has been extended to the manufacture of cooking vats, tanks, and other large vessels for hotels, restaurants, and canning factories. It was estimated that 10,000,000 pounds of aluminum would be used in the United States in 1927 in making mason-jar caps alone (a newly developed use). All sorts of furniture (especially chairs, tables, and cabinets) for use in the home, office, restaurants, and dining cars are being made to compete with similar steel-made products. Specially treated aluminum sheet is being made in Germany and substituted for tinned sheet in canning vegetables and fruits. Much aluminum is made into shingles, corrugated sheet for roofing and siding, and numerous ornamental pieces.

Use in Alloys.—Not all of the aluminum alloys can even be mentioned. Two important ones are *duraluminum*, containing about 96 per cent aluminum, 3 per cent copper, and 1 per cent magnesium; and *aluminum bronze*, 90 per cent copper and 10 per cent aluminum. (Due to the lighter weight of aluminum, its 10 per cent content in aluminum bronze represents 30 per cent of the volume of the alloy.) Duraluminum becomes very hard after annealing. It is about equal to a good bessemer steel in its physical qualities yet is only one-third its weight. Aluminum bronze is not only strong but also is resistant to corrosion, especially by

salt water. In 1927, "alclad," an aluminum alloy that is coated with very pure electrolytic aluminum, was put on the market by the Aluminum Company of America and is finding a ready market, as it is very resistant to corrosive action.

Electrical Uses.—The use of aluminum as an electrical conductor has made marked advances in recent years. Modern long distance conductors or cables are made of six strands of aluminum wire wound around an inner strong steel wire. Wire and other electrical parts are likewise made entirely of aluminum.

Minor Uses.—There is also a long list of minor uses of aluminum. Some of the most important of these are in making collapsible tubes for pastes, greases, and such substances; constructing many radio parts; and as foil. The consumption of aluminum in foil in the United States in 1928 has been estimated at 6,000,000 pounds. The foil was used for wrapping

candies, chewing gum, and yeast cakes; in condensers in radios; and for a variety of other purposes. The tallest radio tower in the world, which is in Germany, is made of aluminum. The metal is also employed in making paints. Aluminum powder has valuable uses as a precipitating agent of the precious metals, in welding by the thermit process, and in making explosives.

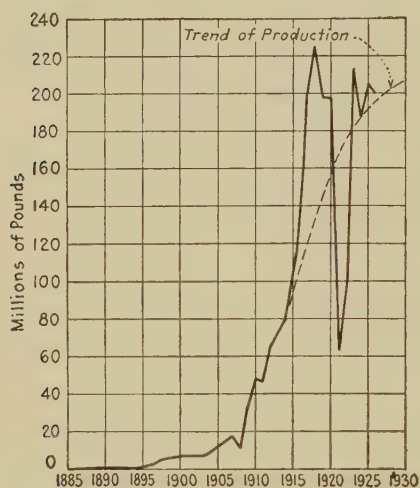


FIG. 122.—Production of aluminum in the United States from 1885 to 1926. (Data from *U. S. Mineral Resources*, 1915, Part 1, and *Mineral Industry*, 1926.)

this production came from Arkansas, and the remainder from Georgia, Alabama, and Tennessee.

In addition to the domestic production, 350,000 long tons of bauxite was imported into the United States in 1928. This bauxite came largely from British and Dutch Guiana, though a considerable tonnage came from several European countries.

The value of new aluminum produced in the United States in 1927 was \$39,266,000; the secondary aluminum recovered was valued at \$23,469,000 (46,200 short tons); and \$14,200,000 worth of metallic aluminum was imported. The production of aluminum in the United States from 1885 to 1928 is shown in Fig. 122.

PRODUCTION OF BAUXITE AND ALUMINUM IN THE UNITED STATES

The total production of bauxite in the United States in 1928 was 375,000 long tons, valued at \$2,273,000. Over 96 per cent of

WORLD PRODUCTION OF ALUMINUM

The estimated world production of aluminum in 1927 is shown in the following table:

TABLE 55.—ESTIMATED WORLD PRODUCTION OF ALUMINUM, 1927¹

Country	Amount, pounds
United States.....	160,000,000
Germany.....	70,000,000
Canada.....	60,000,000
Norway.....	46,000,000
France.....	44,000,000
Switzerland.....	44,000,000
United Kingdom.....	16,000,000
Austria.....	6,000,000
Italy.....	4,000,000
Total.....	450,000,000

¹ ANDERSON, *U. S. Mineral Resources*, 1927, Part 2, p. 18.

Selected Readings on Bauxite and Aluminum

FOX, C. S.: "Bauxite," London, 1927.

CARSON, M. G.: "Aluminum—The Metal and Its Alloys," New York, 1926.

RIES, H.: "Economic Geology," pp. 750–758, John Wiley & Sons, Inc., 1925.

LADOO, R. B.: "Non-Metallic Minerals," pp. 80–90, McGraw-Hill Book Company, Inc., New York, 1925.

HILL, J. M.: *U. S. Mineral Resources*. Annual volumes have considerable material of interest.

McBRIDE, R. S.: "Mineral Industry," pp. 11–47, McGraw-Hill Book Company, Inc., 1926.

MEAD, W. J.: Occurrence and Origin of the Bauxite Deposits of Arkansas, *Econ. Geol.*, vol. X, pp. 28–54, 1915.

SHEARER, H. K.: Bauxite and Fuller's Earth of the Coastal Plain of Georgia, *Geol. Survey Ga. Bull.* 31, 1917.

Light Metals and Alloys—Aluminum, Magnesium, U. S. Bur. Standards *Circ.* 346, 1927.

CHAPTER XI

MINOR METALS

ANTIMONY

Antimony is a cheap metal that finds its principal use as an alloy or as a substitute for some other higher-priced metal. Its abundance in the earth's crust is given by Clarke and Washington as 0.000,0X per cent. It is the second most abundant of the four semimetals: arsenic, antimony, bismuth, and tellurium. Antimony is a very brittle metal, has a bluish-white color, melts at 450°C., and is unacted upon by air or oxygen at ordinary temperatures. Unlike most metals, it expands on solidifying and therefore is used in alloys for making fine and sharp castings.

Mineralogy of Antimony.—The most common and abundant antimony mineral is *stibnite*, Sb_2S_3 , which, when pure, contains 71.4 per cent antimony. Stibnite is the chief source of antimony. The metal occurs also in several copper and silver minerals, from which *complex ores* it is recovered as a by-product. A third source of antimony is *antimonial galena*. Antimony oxides occur, but they are of minor importance as sources. Antimony occurs rarely as the native metal. A few complex antimony minerals are known.

Mode of Occurrence of Antimony Ores.—Stibnite is usually found in deposits near the surface. A few deposits are found near igneous rocks at greater depths. The usual occurrence of stibnite is in quartz veins, but replacement deposits occur, also. The veins occur in various kinds of igneous and sedimentary rocks, but the replacement deposits are usually in calcareous rocks. The stibnite may be accompanied by a few sulfides, such as pyrite, galena, sphalerite, arsenopyrite, and realgar.

Origin of Antimony Ores.—All stibnite deposits are apparently genetically connected with igneous rocks, although the exact origin of a few deposits is doubtful. The deposits are formed under conditions of low temperature and pressure, conditions which permit the formation of beautiful stibnite crystals.

Antimony Deposits. Domestic Deposits.—There are no important antimony deposits in the United States, though there are a number of small ones that can be worked if the market price of antimony is high enough. These were worked during the World War, when the demand for the metal was nearly four times the normal peace-time need, but there has been little domestic production since the war was over.

The antimony deposits in the United States are located near Gillham, Sevier County, *Arkansas*; Battle Mountain and Austin, Lander County, and Lovelocks, Humboldt County, *Nevada*; Burke and Kingston, Shoshone County, *Idaho*; Tonasket, Okanogan County, *Washington*; San Emigdio Cañon, Kern County, *California*; Coyote Creek, Garfield County, *Utah*; and in other states.

Foreign Deposits.—The chief source of antimony for the world is the deposits of *China*. The major part of China's production comes from the large deposits near Changsha, province of Hunan. Hunan, which contains seven important fields, furnishes 90 per cent of the country's output. The most important is the Kai-kong-shan, which is about 3.5 miles long by 2 miles wide. The total reserves for the northern part of this field are estimated at 1,400,000 tons of metallic antimony. The ores occur in a shattered quartzite which is about 160 feet thick. The chief ore mineral is *stibnite*, which occurs in the cracks and fissures of the quartzite. The ore, as a whole, averages about 6 per cent antimony but is hand picked to furnish a 60-per cent ore. The mining and smelting methods used are very primitive.

Bolivia was second in production of antimony in 1927. The deposits are in the southwestern part of the country, in the Chuquitu district near Uncia and in the area around Porco. The ore mineral is *stibnite*. It occurs in quartz veins that cut Paleozoic shales. The reserves of low-grade ore are large.

Mexico has several important deposits of antimony. One of these is in the Altar district in north-central Sonora. This district produced about 33 per cent of Mexico's antimony in 1927. The mines are scattered over an area of 35 square miles. The chief ore minerals are *oxides of antimony*, which occur in veins. Deposits are also known to occur near Hermosillo in central Sonora. Another important district lies in northern San Luis Potosi. The ore of this district is found in a belt about 14 miles long. It occurs in a porphyry and contains from 5 to 55 per cent antimony. Antimony is also produced in Hidalgo, Queretaro, and Lower California.

Uses of Antimony.—For a metal whose annual world production has averaged only about 21,000 tons for the last 9 years, antimony has a surprisingly long list of important uses. A summary of these uses in the United States in 1926 is given in Table 56.

Use in Alloys.—Of all the antimony used in the United States, 80 per cent goes into alloys. A notable feature in the use of antimony alloys is the large percentage of the metal that is recovered and finds its way back into use again. Such conservation should be used more extensively for other metals. Little antimony is recovered, however, from the alloys employed in making collapsible tubes, foil, explosives, and bullets.

TABLE 56.—ESTIMATED PERCENTAGE OF CONSUMPTION OF ANTIMONY BY USES IN THE UNITED STATES, 1926¹

Uses	Percentage amount
Babbitt metal.....	26.0
Battery plates.....	14.0
Soft metal alloys and solder.....	12.0
Hard lead, including pipe, traps, etc.....	10.0
Type and type metal.....	8.0
Vulcanized rubber and rubber goods.....	7.0
Bearing and antifriction metals not elsewhere specified.....	6.5
Enamel on metalware.....	4.0
Cable coverings.....	3.0
Chemicals, paints, and pigments.....	2.5
Brass, including bronze.....	0.8
Shrapnel and other bullets.....	0.5
White metal and alloys, foil, collapsible tubes, britannia metal, caskets, carriage and other hardware and lighting fixtures, primers for explosives, and miscellaneous uses.....	5.7
Total.....	100.0

¹ FURNESS, J. W., *U. S. Mineral Resources*, 1926, Part 1, p. 73.

Though antimony was an important ingredient of the original *babbitt metal*, some babbitt metal is now made that omits it (substituting lead). When a hard alloy for bearings is to be made, however, antimony is used. This alloy possesses antifriction qualities, which is another reason for its use in bearings, as it greatly reduces the friction between the bearing surfaces.

Another important application to which an alloy of antimony is put is in making *battery plates* for storage batteries for automobiles and, to a minor extent, for radios. It was estimated that 190,000 tons of antimonial lead was used in storage batteries in the United States in 1926. During 1927 and 1928, there was a decrease in the amount of the alloy used by radios, due to the fact that radios were then being connected with light sockets. Over 90 per cent of the antimony employed in battery grids is recovered and used again.

Antimonial lead is used also in *pipes*, *traps*, and *shrapnel* and other bullets. Antimony hardens the lead, and this quality in bullets allows them to retain their shape after the bursting of the shell. It is estimated that 180,000 tons of lead containing about 1 per cent antimony is employed annually in the United States for *cable coverings*, with a resultant saving in initial cost and repairs.

The extensive use of antimony in *type metals* of all kinds is due to the fact that it expands on solidifying and contributes this property to its alloys. This makes possible the rapid casting of perfect letters in type-setting machines. Ordinary type metal consists of 4 parts lead to 1 part antimony, with occasionally some tin. Stereotype metal consists of

112 parts lead, 18 parts antimony, and 3 parts tin. *Britannia metal* is a mixture of 140 parts tin, 9 parts antimony, and 3 parts copper and is used for making cheap tableware that resembles pewter.

Non-alloy Uses of Antimony.—Antimony is used in enamels on metalware; in paint pigments, such as white lead; and in vulcanizing rubber. The pentasulfide of antimony, Sb_2S_5 , which is a dark orange-red, is used as a substitute for vermilion red (artificial cinnabar) in coloring rubber. This is on account of the high price of mercury. The antimony in all these uses is largely lost.

Production of Antimony.—The United States did not produce any antimony from ores in 1927. A production of 16,040 tons of antimonial lead, having an antimony content of 1,996 tons, was made from domestic ores that year. This antimonial lead was used directly as an antimony alloy. About 12,000 tons of metallic antimony, antimony ore, and antimony alloys was imported into the United States in 1927, and 12,400 tons of secondary antimony was recovered from alloys, scrap, and other sources.

The world's annual production of metallic antimony in 1927 was about 29,000 short tons, of which China furnished about 80 per cent.

Selected Readings on Antimony

See the annual volumes of *U. S. Mineral Resources* and *Mineral Industry*.

ARSENIC

Arsenic is the most abundant of the four semimetals in the earth's crust. Clarke and Washington give its percentage as 0.000,X. It is the base in some compounds and is in the acid radical in others.

Mineralogy of Arsenic.—Arsenic occurs as *native arsenic*, As; *realgar* AsS ; *orpiment*, As_2S_3 ; *arsenopyrite*, FeAsS ; *enargite*, Cu_3AsS_4 ; and in a number of arsenides in combination with several metals. Arsenopyrite is a hard, silvery-white mineral, of common occurrence in sulfide deposits. It is the most important source of arsenic.

Mode of Occurrence of Arsenic Ores.—Arsenic minerals occur in all types of ore deposits except those of magmatic segregations. Arsenic sulfides are most abundant in the intermediate and shallow deposits, but arsenopyrite occurs commonly in all of them. The widespread occurrence of arsenic is shown by the fact that it combines with copper, lead, zinc, cobalt, nickel, iron, and silver.

Origin of Arsenic Ores.—The widespread occurrence of arsenic minerals in all types of mineral deposits derived from igneous rocks is sufficient evidence that arsenic is a common constituent of magmatic solutions and gases and that magmas were, therefore, the source of the arsenic minerals.

Arsenic Deposits. *Domestic Deposits.*—Very few deposits of arsenic minerals are worked for their arsenic alone. The arsenic minerals occur in the complex lead-copper-silver ores, and the arsenic is recovered as a by-product during the recovery of the other metals. A few fairly rich arsenic vein deposits occur in the eastern part of the United States (one at Bristol, *Virginia*), but none is worked at present (1928) because none can compete with the production of by-product arsenic. The Butte, *Montana*, copper ores are the most important source of arsenic in the United States. The arsenic occurs there in the copper-arsenic mineral enargite. The arsenious oxide (white arsenic) produced by *Utah* comes largely from the complex ores at Tintic.

Foreign Deposits.—Arsenopyrite and other arsenic minerals are found in mineral deposits throughout the world but are saved as by-products in only a few localities. The countries producing arsenic (in the approximate order of production) are *Mexico*, *Japan*, *Canada* (Cobalt), *England* (Cornwall), *Queensland*, *Algeria*, and *Portugal*.

Uses of Arsenic.—The chief use of arsenic is in *insecticides*, largely in the form of calcium arsenate, lead arsenate, and Paris green (a copper acetate and arsenite). In 1926, it was estimated that 75 per cent of the arsenic used in the United States was in insecticides. Large quantities of calcium arsenate are employed in fighting the cotton boll weevil. In 1926, between 17,000 and 18,000 tons was so used in the United States.

The second most important use of arsenic is in *glass making*. No less than 6,000 tons was so used in the United States in 1926. A large part of this amount was employed in plate-glass manufacture. The amount of arsenic used in glass is small: 1 or 2 parts in 160 to 190 parts of all materials. The arsenic aids in the fusion of the "batch" or glass mixture.

The third use of arsenic is in *weed killers* (as sodium arsenite). About 4,000 tons was used for this purpose in the United States in 1926. Smaller quantities were employed in cattle dips and poison baits for rodents and other small animals.

A recently developed use of arsenic is as a *preservative* of wood. This use shows promise of becoming an important one. A number of *chemicals* are made from arsenic, and small amounts of it are used in fireworks (it gives a white light), dyeing, pigments, and medicines. As arsenic is poisonous, substitutes for it are being employed wherever possible. Considerable quantities of arsenic trioxide are used in preserving hides (both by taxidermists and in the leather industry) and as an antiseptic. Potassium arsenite is used as a reducing agent for silver in the manufacture of mirrors.

Arsenic forms *alloys* with various metals. It is used in lead for making shot, because, as it makes the molten lead more fluid, better-formed shot are produced. Several white-metal alloys of arsenic are known, but none is important.

Production and Imports of Arsenic.—The domestic production of arsenious oxide is entirely as a by-product from smelting complex ores. The total production in 1927 was 11,730 tons the average price of which was 3 cents a pound. Smelters of copper ores at Butte, Montana, and Midvale, Utah, were responsible for essentially all of this arsenic production.

The imports of arsenic into the United States exceeded the domestic production in 1927. The larger part of the imports came from Mexico, from the smelter of the American Smelter and Refining Company at San Luis Potosi, which is one of the largest arsenic plants in the world. Other imports were from Canada, Japan, Belgium, and Germany.

Selected Readings on Arsenic

There is very little in the literature on arsenic. *Mineral Industry* contains the most information.

BISMUTH

Bismuth has a number of minor uses, but the total quantity needed annually is small. It is less abundant in the earth's crust than arsenic or antimony but more abundant than tellurium.

Mineralogy of Bismuth.—Bismuth occurs in three or four minerals, but none is abundant or common. *Native bismuth* and *bismuthinite*, Bi_2S_3 , are the chief ore minerals. Like that of arsenic, however, the production of bismuth in the United States and in most of the world is as a by-product.

Mode of Occurrence and Origin of Bismuth Ores.—Bismuth minerals are found in many types of vein deposits, usually in association with lead, silver, and gold ores. All occurrences of bismuth ores are of magmatic origin.

Bismuth Deposits. Domestic Deposits.—There are no important deposits of bismuth in the United States. A bismuth deposit to be rich enough to mine should contain 3 per cent bismuth, and very few do. So, as we have said, the bismuth production comes from other ores. The element is found in the ores at Leadville, *Colorado* (some ore containing 10 per cent bismuth was mined in 1916); Tintic, Little Cottonwood, and San Francisco, *Utah*; Engle, *New Mexico*; Battle Mountain and other places in *Nevada*; Breckenridge, *Colorado*; Yuma County, *Arizona*; and Butte, *Montana*. Some bismuth has been produced at all these localities except Butte, and it has been estimated that 800 pounds of it goes into the air daily from the smelters that treat Butte ores. This amount would be equal to 275 tons of Bi_2O_3 in a year.

Foreign Deposits.—Considerable bismuth is recovered from the tin ores of *Bolivia*. Other important deposits occur in *Spain* and *Japan*, and minor deposits in *Argentina*, *Australia*, and *Canada*.

Uses of Bismuth.—The chief use of bismuth is in various alloys with lead, tin, and cadmium. These alloys have melting points that are much below those of the constituent metals. There are many of these low-fusion alloys on the market, but all contain 42 per cent or more bismuth and varying amounts of lead, tin, and cadmium. The melting point of these metals is as follows: bismuth, 268°C.; lead, 327°C.; tin, 232°C.; and cadmium, 320°C.; yet several of their alloys melt below the boiling point of water, and some can be softened by the heat of the hand. The melting point and composition of some of these alloys are given in the following table:

TABLE 57.—MELTING POINT AND COMPOSITION OF SOME FUSIBLE ALLOYS

Alloy	Melting point	Percentage of			
		Bi	Pb	Sn	Cd
D'Arcet's metal.....	79°C. (174.2°F.)	42.1	42.1	15.8	....
D'Arcet's metal.....	94.5°C. (202.1°F.)	50.0	31.2	18.8	....
Wood's metal.....	60°C. (140.0°F.)	68.2	....	18.2	13.6
Lipowitz's metal.....	65°C. (149.0°F.)	50.0	26.6	13.4	10.0
Rose's metal.....	94°C. (201.2°F.)	50.0	25.0	25.0	....

These fusible alloys are used in automatic water-sprinkler systems in buildings; when the air is heated by a fire, the alloy is fused and the water is thus released. They are also used in electric fuses, safety plugs in boilers, dental amalgams, fuses for hand grenades, and electrottype molds. Some of these alloys of bismuth expand on cooling and are used for making castings of detailed objects. Bismuth wire has an important use in electrical apparatus and for measuring small intensities of heat and light.

Bismuth is extensively used in medical and cosmetic preparations. The smooth unctuous feel of bismuth salts is the characteristic that makes them suitable for cosmetics and also for certain medical preparations. Bismuth nitrate is taken internally before X-ray photographs of the digestive organs are made, as it is opaque to the rays. Bismuth salts are used with oxides of other metals to impart colors to porcelain and with gold for gilding it. Bismuth nitrate gives to porcelain a colorless iridescent glaze. The salt is also used in printing fabrics and in making optical glasses.

Production.—Figures of the exact production of bismuth in the United States are not kept, but the country is second in its production. Bolivia is first; Spain, third; and Japan, fourth. In 1926, the United States used 300,000 pounds of bismuth, 48,000 pounds of which was imported.

Selected Reading on Bismuth

DUNSTAN, B.: Uses of Bismuth, quoted in *U. S. Mineral Resources*, 1917, Part 1, pp. 29-31.

CADMIUM

Cadmium is a rare metal (estimated percentage in the earth's crust is 0.000,0X) that is closely related to zinc and always found in association with it. The word "cadmium" comes from the Latin *cadmia*, which was the name applied to the crust formed in zinc furnaces. This crust contains from 10 to 20 per cent cadmium, due to the fact that the metal volatilizes before zinc and is deposited as the oxide in the cooler portions of the furnace. Cadmium is a bluish-white, lustrous metal, capable of taking a high polish which it retains indefinitely in dry air. It is fairly ductile and can be beaten or rolled into thin foil. It is a little harder than tin but is softer than zinc. Pure cadmium has a peculiar "cry," similar to that of tin, when bent. It has a fibrous structure, and the "cry" is due to these fibers' rubbing each other as the metal is bent. The melting point of cadmium ($320^{\circ}\text{C}.$) is only slightly higher than that of bismuth ($268.3^{\circ}\text{C}.$), and its boiling point ($778^{\circ}\text{C}.$) is lower than that of zinc or bismuth. Cadmium alloys readily with other metals, lowering their fusing points and yet not making them brittle. It even increases the hardness and toughness of copper and silver.

Mineralogy of Cadmium.—There are few cadmium minerals, and the only important one is cadmium sulfide, CdS , which occurs crystalline as *greenockite* and amorphous as *xanthochroite*. *Otavite* is a rare basic cadmium carbonate that has been found only in Southwest Africa. The chief source of cadmium is zinc ores. It is present especially in sphalerite.

Mode of Occurrence and Origin of Cadmium.—Since cadmium is found only with zinc ores, its mode of occurrence is the same as theirs. Not all zinc districts are equally rich in cadmium, hence its production is restricted to a few areas.

Cadmium salts are apparently transported by the same type of solution that transports zinc. We have already seen that zinc deposits are associated with igneous rocks in all parts of the world and were evidently deposited by magmatic waters. A similar origin must, therefore, be true for the associated cadmium.

Domestic Deposits and Treatment of Cadmium Ores.—Although cadmium is found in traces in many zinc deposits in the United States, in only a few is it present in sufficient amounts to pay for collecting and refining it. The commercial supplies in this country are recovered (1) from zinc ores that are treated by fractional distillation (the cadmium volatilizing first is collected from the first fractions given off), (2) from the fumes in the baghouse of smelters treating lead and zinc ores, and (3)

from residues from the purification of zinc solutions. These residues are treated either at the plant treating the zinc ores or at plants specially equipped for recovering cadmium. No less than ten plants in the United States produce cadmium (1928). Five of these are lithopone plants, two are lead smelters, one is a zinc smelter, one is an electrolytic-zinc plant, and one is a chemical and lithopone plant.

The richest cadmium-bearing zinc ores in the United States are those of the *Tri-State area* in Oklahoma, Kansas, and Missouri. No recent studies of the cadmium content of these ores have been prepared, but tests made many years ago indicated an average of 0.358 per cent. A recent estimate is 1 part cadmium to 160 parts zinc. Certain types of ores in *Arkansas* contain higher amounts of cadmium, but they are unimportant quantitatively. The lead ores of *southeastern Missouri* contain a mere trace of cadmium, yet it is concentrated over a period of months in the baghouse of the lead smelters and saved. The zinc ores of *Butte, Montana*, contain cadmium which is recovered in the electrolytic zinc plant of the Anaconda Copper Mining Company. The *Utah* lead and zinc ores also contain cadmium.

Foreign Deposits and Treatment of Cadmium Ores.—The zinc ores of *British Columbia* contain cadmium, and a plant capable of a yearly production of over 350,000 pounds of cadmium was put in operation by the Consolidated Mining and Smelting Company of Canada at Tadanac, British Columbia, in 1928. This plant actually produced 491,894 pounds of the metal in 1928. The Electrolytic Zinc Company's zinc plant at Risdon, southern *Tasmania*, began producing cadmium in 1923 and since then has produced between 300,000 and 400,000 pounds annually. Less than 40,000 pounds of this production came from Tasmanian ores, the larger part being made from Australian zinc ores. The Broken Hill lead-zinc-silver mine of *South Australia* was evidently the chief source of the ore, although definite statements as to this are lacking. The cadmium production from the Risdon plant is expected to be doubled, following an arrangement made early in 1929 whereby the cadmium-bearing residues from the zinc smelters at Port Pirie, South Australia, will go to Risdon for treatment. Cadmium has long been produced from the Silesian zinc deposits, now largely in *Poland*. *Germany* supplied the world's needs for the metal from these deposits before the World War, but since then their production has greatly declined. A little cadmium is recovered in *Great Britain*, *Belgium*, and *France* during the refining of zinc ores.

Uses of Cadmium.—Cadmium has many different uses the chief of which are in low-melting alloys, in plating other metals, in pigments, and in numerous chemicals. Its utilization is a recent development and has not yet (1928) become fully established, first, because other metals can be substituted for it, and, second, because of its high price.

Low-melting Alloys.—Cadmium is a constituent of many of the low-melting bismuth alloys. These cadmium alloys are used for electric fuses; fuse plugs for automatic sprinkler systems, steam boilers, and fire alarms; and as solders. They contain from 1 to 15 per cent cadmium, along with the lead, tin, and bismuth. Lipowitz's metal (a white metal with a luster like polished silver) melts at 60°C. and is used for making casts of small animals. A similar alloy is used for making casts of the human body. Other alloys that melt at even lower temperatures are known. Some are fairly hard and can be bent and worked. Stereotype plates are made of cliché metal, which contains 50 per cent lead, 27.5 per cent tin, and 22.5 per cent cadmium or bismuth. Cadmium is better than bismuth in this alloy, as its use produces a metal capable of giving a greater number of impressions. It is added to lead for cable casings and can be substituted for tin in solders, where 1 pound of cadmium is the equivalent of 3 to 5 pounds of tin.

Hard Alloys.—Cadmium added to copper hardens it (and thus increases its strength and wearing qualities) without reducing its electrical conductivity as most hardening substances do. It is also used to harden silver. Only small quantities are needed for these purposes: 0.5 to 1.2 per cent. Cadmium greatly increases the resistance of silver to tarnishing. Various alloys of silver containing this and other metals have been patented and are used for tableware. Cadmium is also used in making green gold.

Cadmium Plating.—A recently developed use of much interest is cadmium plating. The cadmium protects the metal, chiefly iron, against rusting by forming an alloy with it that is very resistant. The coating is very thin and adhesive and does not peel off like nickel or zinc. Cadmium may be plated on a metal and then covered by another metal, such as nickel, copper, or aluminum, and the resulting product is rust resistant. A large number of small parts of automobiles, such as nuts, bolts, and locks, are being coated with cadmium to prevent their rusting.

Miscellaneous Alloys.—There are numerous miscellaneous uses of cadmium alloys. One use, in storage batteries, is of interest because batteries made of the alloy can be run down and left discharged indefinitely without destroying the plates. As such batteries cost nearly twice the price of ordinary ones, their use is limited, however.

Use in Chemicals and Pigments.—Many cadmium salts are used in chemicals, photographic materials, fireworks, clay products, fluorescent paint, rubber, and soaps; in dyeing and calico printing; and for coloring glass and porcelains. Cadmium salts are poisonous and are not used in medicines. Cadmium sulfide is brilliant yellow; and, used as a pigment, it forms one of the most permanent yellow paints known. It is employed extensively in painting street cars and passenger coaches. Chrome yellows can be substituted, but chrome paints are not so permanent and

are affected by coal smoke. Cadmopone is a yellow pigment prepared by mixing cadmium sulfate with barium sulfide. It forms excellent ivory and cream tints.

Production.—The production of cadmium in the United States passed the 1,000,000-pound mark in 1927. This amount was over 60 per cent of the world's production that year, but with the completion of the new plant at Tadanac, British Columbia, and the doubling of the cadmium production at Risdon, Tasmania, this percentage will decrease.

Cadmium was first made in the United States in 1906, in which year the production was 300 pounds of metallic cadmium. In 1918, it reached 127,000 pounds; in 1923, 183,000 pounds; and since then has increased rapidly. The Anaconda Copper Mining Company alone produced 233,736 pounds of cadmium in 1926. It has been estimated that if the zinc ores in all parts of the world averaged 1 part cadmium to 400 parts zinc, 3,000 tons of cadmium could be produced annually if all the ores were treated for its recovery. Actually, about 1,100 tons are produced, which is about the world's present refinery capacity for producing cadmium. The active demand for the metal accounts for the great increase in its production; but, if its price is raised (as is so often done as soon as there is a demand for a product), the extension of its uses will be curtailed and cheaper metals will be substituted for it.

Selected Readings on Cadmium

TYLER, P. M.: Cadmium, *U. S. Mineral Resources*, 1927, Part 1, pp. 323-339. This is a very good account of the uses of cadmium and the general situation. It has an excellent bibliography. See, also, *U. S. Mineral Resources* for 1908 and 1918.

BUDGEN, N. F.: Cadmium: Its Metallurgy, Properties, and Uses, Griffin and Co., London, 1924.

MAGNESIUM

Magnesium is the lightest metal now known which remains comparatively unaltered under ordinary atmospheric conditions. It has a specific gravity of 1.74. Aluminum is the next lightest durable metal (specific gravity 2.58). Magnesium is silvery white. It has great strength.

Source of Magnesium in the United States.—The magnesium used in the United States is made from magnesium chloride (obtained as a by-product from brines) and from calcined magnesite.

Uses of Magnesium.—The most important use of magnesium is in making castings. Among those made in the United States in 1927 were parts for aircraft, such as crankcases, oil pans, pistons, control pulleys, gasoline-line fittings, bearings, instrument parts, control levers, hinges, and steps. Other magnesium castings are microscope parts, lens holders, field glasses, parts of moving-picture machines, surveying instruments, golf-club heads, artificial limbs, impellers for air compressors, shuttles, and special bobbins. Sheet and plate magnesium of excel-

lent quality are now made, also, and find uses as linings for airplanes and pilot boats for dirigibles and in making radio diaphragms, resonating disks for automobile horns, and radio rectifiers. Rods and tubing of magnesium have many uses, such as in instruments, parts of airplanes, and any place where very light weight is desired. Magnesium ribbon and wire of various sizes are made, and their chief use is in degasification of radio tubes. Magnesium, as a deoxidizer and desulfurizer, has a wide application in the production of other metals, especially nickel, monel metal, brass, and bronze.

Numerous magnesium alloys are made, especially those with aluminum, which are used for aircraft parts. Magnesium-aluminum alloys that are light (specific gravity ranging from 1.7 to 1.9) and have high strength are finding a wider market each year. Only 0.5 per cent magnesium is used in many of these. An alloy containing 93 per cent magnesium, 7 per cent aluminum, and 0.04 per cent manganese has been developed, and castings made of it have a tensile strength of 30,000 pounds per square inch and an elongation of 8 to 10 per cent. Lead for telegraph and telephone cables is hardened by 0.04 per cent magnesium. Another alloy that is attracting attention because of its light weight and great strength is composed of magnesium and beryllium. Beryllium has only recently been separated in a metallic form suitable to be alloyed. It has a specific gravity of 1.93; hence, this magnesium-beryllium alloy should be one of the lightest it is possible to make. Beryllium sells for \$200 per pound. Magnesium is widely used as a flash-light powder and for burning to secure a brilliant white light. A magnesium powder of large bulk and low specific gravity is now made and is being tried out as a vulcanizer of rubber.

Production.—The production of metallic magnesium in the United States began in 1915, that used previously having been imported. The production increased rapidly until 1918, then decreased until 1921, and since has steadily increased. It reached a maximum in 1928, when 483,000 pounds of magnesium was produced, valued at \$587,000. Ingot magnesium sold for \$0.82 per pound in 1928, the powder for \$1.51 per pound, and castings for \$2.39 per pound. The United States is still far behind Europe in the production and use of magnesium. Over 5,000,000 pounds was produced and used in Europe in 1927.

MERCURY

Mercury is one of the rare elements of the earth's crust (0.000,0X per cent), and yet it was known to ancient man, for Theophrastus (374–287 B.C.) refers to a “liquid silver” obtained by rubbing cinnabar with vinegar in a copper vessel. “Cinnabar” comes from the Greek word for mercury sulfide. “Quicksilver,” a popular name for mercury, comes from two Anglo-Saxon words: *cwic*, living, and *seolfor*, silver. Mercury is the

only common metal that is liquid at ordinary temperatures, a property that makes it useful for many purposes for which there are no substitutes. Although a liquid itself, mercurial compounds are solids. The annual world production of mercury has ranged between 3,000 and 4,000 metric tons for several years, but in 1928 it exceeded 5,000 metric tons. Mercury is sold in wrought iron or steel flasks that hold 75 pounds.

Mercury is silver-white and has a metallic luster. It freezes at $-39^{\circ}\text{C}.$, becoming a white, malleable, ductile metal. The specific gravity of the liquid is 13.59 and of the solid, 14.19. Mercury boils at 357 and vaporizes at $360^{\circ}\text{C}.$

Mineralogy of Mercury.—The chief source of mercury is *cinnabar*, HgS , which contains 86.2 per cent. Rarely, *native mercury* is found with cinnabar. *Metacinnabarite* (same composition as cinnabar) and *calomel*, HgCl_2 , are found in some deposits. There are also a number of rare mercury minerals. Associated gangue minerals of mercury ores are calcite, chalcedony, opal, quartz, marcasite, pyrite, barite, and rarely stibnite and arsenic minerals.

Physical Properties of Cinnabar.—Cinnabar is vermilion red and has an adamantine luster. Its hardness is 2.5, and its specific gravity, 8.1. It occurs in crystalline masses but may also be earthy.

Metallurgy and Tenor of Mercury Ores.—Mercury is extracted from its ores by distillation. The method varies in different localities, but retorts or vertical or rotary furnaces are usually used in the process. The mercury volatilizes, and the gas is condensed to a liquid in suitable chambers. The simplicity of the metallurgical treatment makes it possible to work very low-grade ores. The average tenor of all the mercury ores mined in the United States in 1926 was 0.54 per cent, which is far below the value of the ores of Spain, the world's leading producer of the metal.

Mode of Occurrence of Mercury Ores.—Mercury ores are especially characteristic of the shallow vein zone. They are found typically in fissured zones and are more common in areas of late Tertiary volcanic activity than in those of older rocks. Some deposits occur in pre-Cambrian rocks, however, but the age of such deposits is unknown and so may be Tertiary. A few are unassociated with igneous rocks at the surface. Mercury ores are usually in fissure veins or disseminated deposits. Both types of deposits occur in sandstones, quartzites, shales, limestones, serpentine, various felsites and porphyries, tuffs, and schists. The best mercury ores occur near the surface.

Origin of Mercury Deposits.—The intimate association of mercury deposits with igneous rocks indicates a magmatic origin for the deposits, as does also their common occurrence in regions of hot springs and other evidences of recent volcanic activity. Hot springs at Steamboat Springs, Nevada, are depositing mercury at present. The gangue minerals and

the character of mercury deposits indicate shallow deposition by hot solutions. Although igneous rocks are not associated with all the deposits, the mineralogy and mode of occurrence of such deposits point to a magmatic source, probably a hidden mass below.

Domestic Mercury Deposits.—The mercury deposits of the United States are in the western states. California has the most important

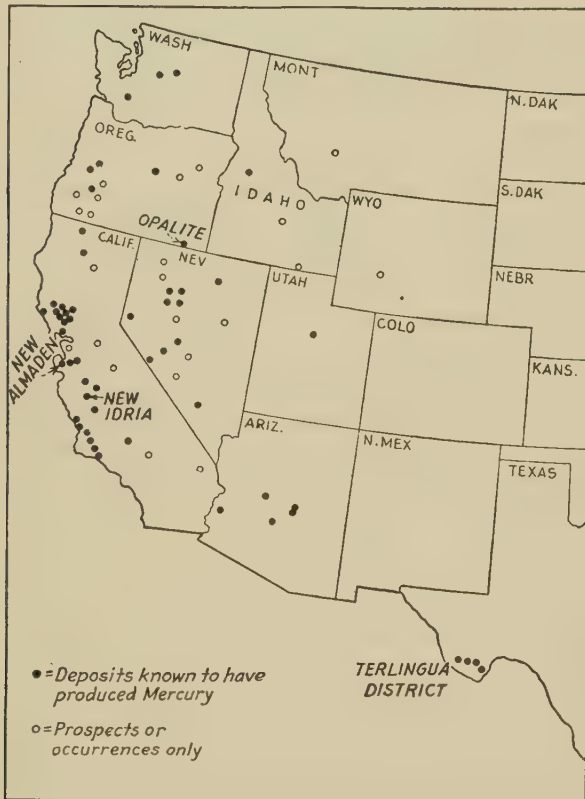


FIG. 123.—Map showing the location of the mercury deposits of the United States. (After Ransome, *U. S. Mineral Resources*, 1917, Part 1 pl. 3.)

deposits, followed by Nevada, Oregon, Texas, Washington, Arizona, and a few others (see Fig. 123).

California.—The principal mercury deposits of California are in a belt 400 miles long and 75 miles wide, that extends from Santa Barbara County on the south to Lake County on the north. The deposits were discovered in 1850, and since then more than 75 mines have been opened. In 1927, only 9 were producing. The cinnabar occurs in veins or as disseminated deposits, both occurring dominantly in serpentine but also

in sandstones and cherts of the Franciscan group. A few deposits are in other rocks, and a few occur outside the main belt. The properties productive in 1927 were scattered throughout the belt.

By far the most outstanding mine in the district is the New Idria in San Benito County, about 140 miles southeast of San Francisco. This mine has been worked continuously since 1853, save for a short period between 1920 and 1922, during which time the property changed owners. Today (1928), it is the largest mercury mine in the United States and the third largest in the world. The ore occurs as veinlets and disseminations in sandstone and shale of the Franciscan group. The mineralized area (an ore shoot) is about 800 feet long and 300 feet wide. It has been mined down to the 1,200-foot level.

Although now closed, the New Almaden mine in Santa Clara County is worth mentioning because of its great production and interesting history. The deposit was discovered in 1824 (Indians are said to have secured cinnabar from it before that time), but the mine did not become a producer of mercury until 1846, when the yield was 2,000 pounds. The mine reached its peak of production in 1865 with 47,194 flasks of mercury. It attained a remarkable depth for a mercury mine, *i.e.*, 2,450 feet, being by far the deepest in the world. It contains more than 84 miles of underground workings. The total production of the New Almaden to the end of 1926, when the mine was closed, is estimated at 1,058,635 flasks of mercury, valued at \$65,000,000 to \$75,000,000. Only one other mine in the world has surpassed this one, and that is the Almaden in Spain.

Nevada.—Mercury is or has been mined in Elko, Esmeralda, Humboldt, Lander, Mineral, Nye, and Pershing counties, Nevada. The deposits are in Tertiary felsites and various sedimentary rocks. They are the typical veinlet deposits or disseminations in intensely fissured rocks. The chief producing mines in 1928 were those of the Nevada Quicksilver and Pershing Quicksilver Companies in Pershing County.

Texas.—The production of mercury in Texas all comes from the Terlingua district in Brewster County. The deposits, which have been worked since 1899, cover a known area of 3 by 7 miles, and may be larger. The district is in an arid region, about 100 miles from a railroad. The formations of the area are Upper and Lower Cretaceous limestones and shales, which are cut by porphyries. The cinnabar ore occurs along a fault zone that strikes nearly east and west. Some of the mines are 750 feet deep and have extensive underground workings. The ore is of low grade, containing about 0.5 per cent mercury.

Oregon.—Ten or twelve deposits of mercury are known in Oregon, but only two or three are important. Most of the production comes from one mine, the Opalite, in Malheur County in the southwest corner of the state. Freight has to be hauled overland nearly 100 miles from

Winnemucca, Nevada. The ore at the Opalite mine is chiefly cinnabar and occurs in a tuff which is largely altered to chalcedony. It averages 0.44 per cent mercury. The total reserves are not large.

Washington and Arizona.—Washington and Arizona made a small production of mercury in 1928 and can be expected to increase this in the future, as retorts were being installed at several properties during 1927 and 1928.

Foreign Mercury Deposits.—The most important mercury deposits in the world are those of the Almaden district in the province of Ciudad Real, Spain; and of two districts in Italy: the Monte Amiata district near Siena in Tuscany and the Trieste district containing the Royal Idria mine. Other countries producing mercury are *Mexico, Russia, Czechoslovakia, and Austria.*

Almaden District, Spain.—The Almaden district contains the most important mercury deposits in the world. Mercury has been mined there for centuries. The Romans are said to have secured it from the area, and mention is made of the deposits in the writings of Theophrastus. The Almaden mine, from which most of the production comes, has been worked for hundreds of years and contains the largest and richest mercury ore body in the world today. The ore body is a quartzite impregnated with cinnabar. It lies between two beds of slate. In 1926, the tenor of the ore was 5.25 per cent mercury. The mine was being worked that year on the thirteenth level, but the ore body there is only slightly smaller and is of higher grade than it was on the level above.

Monte Amiata District, Italy.—The next most important mercury district is the Monte Amiata district in Tuscany, Italy. The Abbadia-San Salvador mine of this district is the second largest mercury mine in the world. The tenor of the ore is much less than that of the Almaden mine. It averaged, in 1926, 1.18 per cent mercury. The ore mineral is cinnabar, and the ore bodies occur in limestones and shales near their contact with a felsitic rock.

Uses of Mercury. *Mercury Salts.*—The chief uses of mercury are in the manufacture of mercury salts to be used as drugs and chemicals. These compounds are many, but the most important are mercuric chloride, HgCl_2 (corrosive sublimate); calomel, HgCl ; and mercuric oxide, HgO . Corrosive sublimate is a widely used antiseptic; and calomel, a well-known medicine. The mercuric oxide, or red precipitate, is used in antifouling paints on ship bottoms. The red oxide unites with chlorine of the sea water to form corrosive sublimate, which is poisonous and kills the barnacles that attach themselves to the bottoms of ships. Other uses of mercury salts are in making fulminating caps for explosives. Vermilion red is artificial cinnabar and is used in red pigments. Over 340,000 pounds of it was manufactured in the United States in 1926, and 175,000 pounds was imported. One of its uses is in coloring rubber,

but in recent years antimony sulphurette has been introduced as a substitute, and it, in turn, is being replaced by organic dyes.

Metallic Mercury.—Metallic mercury has many interesting uses, but none of them requires a very large quantity. It is used in thermometers; scientific instruments; and in electrical apparatus, such as are rectifiers, electric refrigerators, control apparatus, electrical switches, thermostats for oil burners, and automatic controls for electric motors. The former extensive use of mercury in the recovery of gold and silver has been greatly curtailed by the use of other methods, but a considerable quantity is still employed for this purpose. As most of the mercury used in this process is recovered and used over, again and again, the annual requirements are merely to replace the losses. The use of mercury on the back of glass for mirrors is also falling off, as tin is being substituted. A small quantity of mercury is used in dry cells. The lights in many lighthouses are floated on it. The possibilities of employing mercury vapor in power generation are great, but as yet only a few plants in the United States make such use of it. In these plants, however, there is evidence of a higher degree of efficiency than is attained in steam power plants, and once installed there is very little waste of mercury.

Production.—The production of mercury in the United States amounted to 18,108 flasks in 1928. This was the largest output made in the United States since 1919, but it is much smaller than was the average annual production between 1850 and 1921. That in 1921 and 1922 was only slightly over 6,300 flasks. In 1928, 15,583 flasks of mercury was imported. The control of the world mercury market is practically in the hands of Spain and Italy, for they produce about 90 per cent of the world production. There is no evidence of other important deposits in the United States, as no new discoveries of rich deposits have been made for years; so it seems probable that we shall be dependent upon foreign sources for half or even more of our supplies of mercury in the future.

Selected Readings on Mercury

FURNESS, J. W.: *U. S. Mineral Resources*, 1927, Part 1, pp. 51–74.

—: *The Marketing of Mercury*, U. S. Dept. Commerce *Trade Information Bull.* 631.

RANSOME, F. L.: *U. S. Mineral Resources*, 1917, Part 1, pp. 367–455. Has maps of domestic and foreign deposits, as well as a fine bibliography.

—: *U. S. Mineral Resources*, 1918, Part 1, pp. 143–182. Has list of mines of United States in 1918.

PLATINUM AND RELATED METALS

Platinum is one of a group of rare metals all of which are valuable because of their physical properties. The group includes platinum, osmium, iridium, palladium, ruthenium, and rhodium. Platinum is the

most abundant mineral of the group. Its percentage in the earth's crust is estimated by Clarke and Washington as 0.000,000,X, or about the same as that of gold. Iridium and osmium are estimated at 0.000,-000,0X per cent of the earth's crust, and palladium, rhodium, and ruthenium at 0.000,000,00X per cent. All six metals are found associated in the same deposits; in fact, native platinum always contains varying amounts of the other five. Because of this, they are commonly called the "platinum metals." When one element is especially abundant in these natural alloys, this is indicated in the name, as "platiniridium," or "osmiridium."

The atomic weights, specific gravities, and fusing points of these metals are given in the following table:

TABLE 58.—THE MINERALS OF THE PLATINUM GROUP

Element and symbol	Atomic weight	Specific gravity	Fusing points, degrees centigrade
Ruthenium, Ru.....	101.7	12.26	c. 2,400
Rhodium, Rh.....	103.0	12.10	1,950
Palladium, Pd.....	106.0	11.40	1,549
Osmium, Os.....	191.0	22.47	c. 2,700
Iridium, Ir.....	193.0	22.38	2,375
Platinum, Pt.....	194.8	21.50	1,755

Osmium, iridium, and platinum are the three heaviest elements known. With the exception of palladium, which dissolves in hot nitric acid, the other metals of the group are insoluble in ordinary acids, though osmium, platinum, and ruthenium are attacked by aqua regia. Because of their insolubility and high fusing points, these metals are extensively used for chemical apparatus. Iridium is said to be the hardest known metal, and osmium, as we have seen, is the heaviest.

Mineralogy.—The mineralogy of the platinum metals is simple, for they occur native as alloys. The platinum from Colombia, South America, contains 96.2 per cent platinum, 1.1 per cent iridium, 0.5 per cent palladium, and 1.4 per cent rhodium, ruthenium, and osmium. The Russian platinum contains 83.5 per cent platinum, 1.9 per cent palladium, 1.9 per cent iridium, 3.0 per cent osmium, and 0.6 per cent rhodium, ruthenium, and other metals. Platinum occurs as the arsenide *sperrylite*, PtAs_2 , and ruthenium and osmium as *laurite*, thought to be $(\text{RuOs})\text{S}_2$. It seems probable that palladium also occurs as the arsenide in the Sudbury nickel deposits, as it is about as abundant in them as platinum, which occurs as *sperrylite*. A palladium antimonide has recently been discovered in South Africa.

Mode of Occurrence of Platinum Ores.—Most of the world's production of the platinum metals comes from placers that were derived from

the weathering of magnesian-rich rocks. The weight, hardness, and insolubility of these metals favor their concentration in placers.

The metals also occur in certain sulfide ores, as at Sudbury, Canada; the Rambler mine in Wyoming; and the Merensky reef in South Africa. Nickel-bearing pyrrhotite and pentlandite are commonly associated minerals in these sulfide deposits. The ore minerals occur disseminated and as masses in the igneous rocks. Very few vein deposits of platinum minerals are known.

Origin of Platinum Ores.—According to Vogt,¹ “ore deposits carrying noteworthy contents of platinum (or platinum metals) are, with some few exceptions, formed by magmatic concentration.” He groups the principal deposits of the platinum metals under two heads according to origin, as follows:

1. Primary deposits of native platinum metals in dunite (an igneous rock composed essentially of olivine). Examples are the deposits of the Ural Mountains and of the Bushveld igneous complex of South Africa.

2. As magmatic segregations with nickeliferous pyrrhotite in norite. Examples are the deposits at Sudbury, Canada, and the Merensky deposits in the Bushveld area in South Africa.

Deposits of Platinum. *Domestic Deposits.*—There are no important platinum deposits in the United States. The small amount produced is obtained chiefly as a by-product from the gold-dredge operations along the streams at the western base of the Sierra Nevada Mountains. The quantity recovered is small: 299 ounces in 1928. The beach placers in southwestern Oregon also make a small production. A small quantity of platinum occurs with the copper ore at the Rambler Mine, Carbon County, Wyoming, and in a copper-nickel mine near Bunkerville, Clark County, Nevada. These deposits are worked spasmodically, and their production of platinum is insignificant.

Foreign Deposits.—Nearly half of the world's supply of the platinum metals comes from the placer deposits on both the east and west slopes of the central Ural Mountains. The richest deposits are in Siberia. The platinum was derived from the weathering of a magnesian-rich rock, dunite. *Russia* is estimated to have a reserve of 7,000,000 ounces of platinum.

The next largest producer of platinum is *Colombia* in South America. The platinum of Colombia is derived from river gravels occurring chiefly along the head waters of the Rio San Juan and its tributaries and the head waters of the Rio Atrato. Both streams are along the western coast, although the latter flows into the Caribbean Sea. The platinum is believed to come from the weathering of a gabbro located on the divide between the two rivers.

¹ VOGT, J. H. L., *Geology of the Platinum Metals*, *Econ. Geol.*, vol. XXII, pp. 321–355, 1927.

Important deposits of the platinum metals have recently been discovered in *South Africa*. The production from these deposits has increased rapidly, so that in 1928 South Africa was vying with Canada for third place as a producer of platinum.

The nickel-copper ores of Sudbury, *Canada*, are important producers of platinum, palladium, ruthenium, osmium, and iridium. All the metals are saved as by-products. The value of the production of these metals in 1928 was \$1,309,923 (see also p. 134).

Australia makes an important production of osmiridium, principally from the Adams River field in western Tasmania. The ores were discovered in 1925, and at one time 2,000 men were working in the field. The richer gravels have already (1928) been exhausted.

A little platinum is produced in *Japan* and a few other countries.

Uses of Platinum Minerals.—The insolubility, hardness, and high fusing points of the platinum metals give them a wide field of usefulness. They are indispensable for certain chemical purposes; and, because of their high price, the search for substitutes is very persistent. In the electrical field, one-half of the normal demand for platinum is now being met by substitutes. An interesting example of a substitution is the use of vanadium pentoxide, V_2O_5 , in the manufacture of sulfuric acid. The prediction has been made that in 10 years it will have supplanted platinum for this purpose. The following table shows the distribution by uses of the various platinum metals in the United States in 1918 (the last year of the World War) and in 1928:

TABLE 59.—PLATINUM METALS USED IN THE UNITED STATES IN THE VARIOUS INDUSTRIES, 1918 AND 1928¹

Industry 1918	Platinum, ounces	Iridium, ounces	Palladium, ounces	Others, ounces	Total amount, ounces	Percent- age of total
Chemical.....	45,391	717	834	.....	46,942	41
Electrical.....	24,982	3,107	594	.....	28,683	25
Dental.....	11,461	418	7,371	.....	19,250	17
Jewelry.....	13,541	721	42	.....	14,304	12
Miscellaneous.....	5,435	339	212	.....	5,986	5
Total.....	100,810	5,302	9,053	.....	115,165	100
1928						
Chemical.....	18,529	113	1,252	135	20,029	11
Electrical.....	21,316	1,525	9,150	2	31,993	17
Dental.....	10,993	167	12,270	10	23,377	12
Jewelry.....	93,468	3,260	4,965	815	102,508	55
Miscellaneous.....	5,431	963	2,136	850	9,380	5
Total.....	149,674	6,028	29,773	1,812	187,287	100

¹ Data U. S. Mineral Resources.

The striking change that is seen from this table is the difference in the amounts of platinum used chemically and for jewelry in the different years. It should be noted, also, that this change had taken place to almost the same extent in 1919, the very next year after the war.

Chemical Uses.—The chemical uses of platinum are largely as chemical laboratory ware, such as crucibles, evaporating dishes, and triangles, and as chemicals. Substitutes that are cheaper and quite as efficient are finding their way into this field, however. Among these are nickel, nickel-chrome, gold, silica, sillimanite, and palladium.

Electrical Uses.—The use of the platinum metals in electrical instruments and devices is extensive, in spite of the substitution of other metals for them. A change noticeable in 1928 was the increase in the use of the cheaper palladium (\$46 per troy ounce as compared to \$79 for platinum) in the electrical industry. In 1927, 2,491 ounces of palladium was used in this field, and in 1928, 9,150 ounces, or nearly half as much palladium as platinum.

Use in Dentistry.—More than half of the total amount of platinum metals used in dentistry in 1928 was palladium; in fact, the dental industry is the largest consumer of this metal.

Use in Jewelry.—Jewelry has consumed from 55 to 67 per cent of the platinum used in the United States for several years. The chief reason for its extensive use for this purpose is its high price. The price of platinum 20 years ago was but slightly more than that of gold. The great demand for it in the chemical industry caused its price to rise greatly. At one time, it sold for nearly \$120 per troy ounce, or about six times the price of gold. It was then adopted for use in jewelry. This use of platinum in jewelry has caused its employment in the essential chemical industry to fall to one of its least, having led to the substitution of so many other substances. If, therefore, the price of platinum were now to fall, there would be no market for it, as it would no longer be desired for jewelry if it were cheap. It is strange that a metal so closely resembling the disdained silver in appearance should be so highly prized just because it is valuable; this is evidence that beauty is not an essential factor in its use in jewelry. The hardness of platinum and its ability to retain a polish do make it more valuable than gold or silver as a mounting for precious stones. White gold and a gold-platinum alloy that resemble platinum have been put on the market as substitutes for it. As a result, laws are being enacted to control the prices on such wares to prevent their being sold for pure platinum.

Miscellaneous Uses.—The platinum metals have many miscellaneous uses. The ductility of platinum readily permits its being drawn into wires 0.0005 inch in diameter. By the Wollaston method, platinum wires 0.00005 inch in diameter can be drawn. This method consists of inserting a wire of one metal into a tube of another, drawing down both,

and then dissolving the outside metal. Seven ounces of platinum can be drawn into a wire that would reach from New York to London.

Palladium is employed in white-gold alloys, but the recent laws regarding substitutes for platinum are curtailing its use in jewelry. Palladium-gold alloys are proving very satisfactory for dental uses. Palladium is used instead of platinum in solders, in watchmaking, and in making various scientific instruments.

Iridium is very hard and so is used to harden platinum and other metals. It is employed in making scientific instruments where a hard metal is needed, as in the knife edges in balances and the points in pivots, contact points, and pen points, although the usual metal in pen points is osmiridium. Iridium black (an oxide of the metal) is a valuable pigment for decorating chinaware. Osmium has a few uses in alloys and several chemical uses. The other metals have few.

Production and Price of Platinum Metals.—The production of the platinum metals in the United States is unimportant, the total in 1928 being 365 troy ounces. The refiners produced 59,000 ounces from imported ores and concentrates, and the production of secondary platinum metals in the country amounted to 55,831 troy ounces. There was imported in 1928, 135,233 troy ounces of platinum metals, valued at \$9,357,000. Platinum sold for nearly \$79 per troy ounce in 1928; iridium averaged about \$294 an ounce; palladium, about \$46; rhodium, about \$50; osmium, about \$65; and ruthenium, a few dollars cheaper than osmium. Too much platinum was on the market, and, as a result, 8 per cent less of it was used for jewelry in 1928 than in 1927 because it was cheaper.

Selected Readings on Platinum Metals

HILL, J. M.: *U. S. Mineral Resources*.

KUNZ, G. F.: *Mineral Industry*, pp. 530-549, 1926. Also other years.

VOGT, J. H. L.: *Geology of the Platinum Metals*, *Econ. Geol.*, vol. XXII, pp. 321-355, 1927.

SELENIUM

Selenium is a rare member of the sulfur-selenium-tellurium group. Its estimated abundance in the earth's crust is the same as that for bismuth or silver, *i.e.*, 0 000,00X per cent. It is closely related to sulfur and is most commonly found in small quantities in a number of sulfides, especially those of lead, silver, mercury, copper, and bismuth. It is produced in the United States from the anode slimes formed during the electrolytic refining of copper. The commercial material is a grey, metallic-looking substance, which is sold in small pigs or bars. Selenium conducts electricity when exposed to light but only very slightly in the dark.

Uses of Selenium.—The chief use of selenium has been for making "ruby" glass, but it is also employed as a decolorizer for the green color

due to iron. It is used in making red enamels. Its ability to conduct electricity when exposed to light has led to its use in automatic devices for lightings buoys, street lights, electric signs, and burglar alarms. Selenium "has been used in experiments in telephoning along a ray of light and for transmitting sounds and pictures to a distance along a wire."¹ Recently, several important electrical devices that make use of selenium have been put on the market, among them a selenium cell. Another important use of the metal is with sulfur for vulcanizing rubber.

A considerable number of selenium compounds are used as drugs; in photographic materials; and in dyes. A device has been perfected to measure the concentration of mercury vapor through the reaction of selenium sulfide and the vapor. This is done to detect the presence of the poisonous mercury vapor in the air, especially in industrial plants using the vapor. Selenium dioxide has an odor like "rotten horseradish," and endeavors are being made to use it as a stench material in non-odorous poisonous gases.

Production.—In 1927, three companies in the United States produced selenium. All made the production from refining copper ores. Some years ago, a study of the content of blister copper from various localities showed 14 to 170 pounds of selenium per 100 tons of blister copper. Copper from many localities shows traces of selenium. Selenium could also be saved from the flues of the sulfur burners used in making sulfuric acid, but evidently there have been no attempts to do this. The selenium production in the United States in 1927 was 377,278 pounds, which was a sevenfold increase since 1921. The average price of the metal in 1927 was \$1.73 per pound.

Selected Readings on Selenium

HESS, F. L.: Selenium, *U. S. Mineral Resources*, 1914, Part 1, pp. 969-974.
See, also, *Mineral Industry*.

TANTALUM

Tantalum is a very rare metal. Berg estimates its average percentage in the earth's crust at 0.000,001,2. No large or important tantalum deposits are known, and the amount used is obtained from two localities: one in West Australia and the other in the Black Hills of South Dakota. Although the metal possesses many interesting and unusual properties, it has few uses. It always occurs with columbium, from which it is far more difficult to separate than are the platinum metals from one another or than gold is from silver. Only material high in tantalum is desired by manufacturers, as columbium has essentially no uses. When cold, tantalum is resistant to all acids but hydrofluoric; but when red hot, the metal has a remarkable affinity for oxygen and carbon, readily forming the oxide and carbide. For this reason, tantalum is used where it will

¹ HESS, F. L., *U. S. Mineral Resources*, 1914, Part 1, p. 974.

be cold. It is as hard as soft steel but has a greater tensile strength. Because of this tensile strength, it can be hammered into very thin sheets and drawn into fine wires. The wire will support a weight of 93 kilograms per square millimeter, and a good steel wire will support only 70 to 80 kilograms per square millimeter. The metal is greatly toughened by annealing, a process which is accomplished by repeated heating and hammering. It becomes so tough that a sheet 1 millimeter thick was drilled for 3 days with a diamond drill revolving 5,000 times per minute, yet the diamond penetrated only $\frac{1}{4}$ millimeter and was badly worn.

Mineralogy of Tantalum.—Tantalum occurs in *tantalite*, $(\text{FeMn})\text{-Ta}_2\text{O}_6$; *columbite*, $(\text{FeMn})(\text{Cb,Ta})_2\text{O}_6$; and a series of minor tantalates and columbates. The amount of the two elements, tantalum and columbium, varies in different minerals. *Manganotantalite* is one of the most important sources of the metal at present (1928). Antimony, calcium, and tin, as well as traces of many other elements, occur in these minerals. Most of the minerals are black or dark-colored and are hard and heavy.

Mode of Occurrence and Origin of Tantalum.—All tantalum minerals occur in pegmatites and usually only in those in which albite has replaced the first minerals deposited. Small quantities of the tantalum minerals occur scattered through the albite and other minerals. The tantalite and columbite were introduced by the solutions along with the albite. Most of the tantalum minerals are recovered from the weathered parts of pegmatites or are saved during the mining of other minerals.

Deposits of Tantalum Minerals.—The most important deposits of tantalum occur near the Pilbara gold field in *Western Australia*. Though the ore occurs in pegmatites, it is recovered largely from residual detrital deposits and, to a lesser extent, from the dikes. The ores are low in columbium and are, therefore, the more valuable.

The only other producing area of tantalum is near Keystone in the Black Hills, *South Dakota*. The Etta, Peerless, and Ingersoll pegmatites are the most productive. The chief mineral is columbite, containing however, only 45 per cent Ta_2O_5 . This is not so desirable as tantalite as a source of tantalum.

Columbite is found in small quantities in Colorado, the Carolinas, Georgia, Alabama, Virginia, New Mexico, Texas, and California. Tantalite is found in Georgia and South Dakota.

Uses of Tantalum.—Tantalum is used for making chemical ware that does not need to be heated, as it withstands all acids except hydrofluoric. It was formerly used for filaments in incandescent light bulbs but has been entirely replaced for that purpose by the much superior tungsten filament. Tantalum allows an electric current to flow in one direction only, and this property has been utilized in certain electric cells. A recently developed use of the metal is in radio and power tubes.

Pens are made from it. Numerous alloys of tantalum with nickel, tungsten, molybdenum, chromium, aluminum, and iron have been made. Surgical and dental instruments and physical and chemical apparatus are manufactured from these alloys. Various colors can be produced on tantalum, and, as a result, many articles of jewelry are being made from it. One tantalum-steel alloy is used for making springs, saws, and gun barrels. A high-speed tool steel is made from an alloy of iron, tungsten, chromium, and 1 to 3 per cent tantalum and columbium.

Production.—Western Australia exported 17 long tons of tantalum minerals in 1927, and the Black Hills produced about half a ton of columbite. Ferro-alloys containing tantalum to the amount of 15,119 pounds, valued at \$20,012, were imported into the United States in 1927. Tantalum was quoted at \$200 per kilogram (nearly \$100 per pound) in 1927.

Selected Readings on Tantalum

HESS, F. L.: *U. S. Mineral Resources*, 1906, Part 1, p. 532; 1927, Part 1, pp. 406–413. Tantalum a Rival for Platinum, *Eng. and Min. Jour.*, vol. CXXIII, p. 188, 1927.

TELLURIUM

Tellurium is not only a rare metal (percentage estimates of its relative abundance in the earth's crust are placed between those of platinum and gold, though the figure for all three is 0.000,000,X), but it is also of very minor economic importance. It is closely related to selenium and sulfur in many of its properties and occurs in a few minerals with both of these elements. It is the only element that forms important (in amount) compounds with gold, with which it occurs in *sylvanite* and *calaverite*. Both minerals contain silver, also, in varying amounts, and the formula for both is generally written (Au,Ag)Te₂. Tellurium likewise occurs as the oxide. Veins of *native tellurium* $\frac{1}{2}$ inch wide occur at the Good Hope mine, Vulcan, Colorado. Tellurium is more abundant than selenium in ores in the United States, as it occurs in large quantities at Cripple Creek, Colorado (where the chief ore mineral is a gold telluride), and in other mining districts. If there was a sufficient market for it, several tons could be saved annually at the smelters treating the Cripple Creek ores. As it is, the tellurium produced is recovered from the slimes formed during the electrolytic refining of copper. If the tellurium was saved at all copper refineries in the United States, the quantity produced would exceed that which could be obtained from the Cripple Creek ores. The amount recovered from refining blister copper ranges from 3.33 to 67.1 pounds per 100 tons of the copper. The copper of Butte, Montana, contains from 28 to 38 pounds of tellurium per 100 tons.

The tellurium sold is used largely for experimental purposes. The total output in the United States in 1927 was 1,659 pounds. Only 1,003

pounds, valued at \$1,913, was sold. Tellurium gives a peculiar reddish tint to glass. Experiments have been made in alloying it, and one alloy with aluminum is claimed to have a high tensile strength.

Selected Readings on Tellurium

HESS, F. L.: Tellurium, *U. S. Mineral Resources*, 1914, Part 1, pp. 975-977.
See, also, *Mineral Industry* for various years.

URANIUM AND RADIUM

Uranium and radium are discussed together because radium is derived from uranium minerals. Uranium is estimated to rank next to copper in abundance in the earth's crust and to be more abundant than zinc or lead. Its percentage amount is 0.008. Radium is one of the extremely rare metals, its estimated amount in the earth's crust being 0.000,000,000,X per cent or even less. Both uranium and radium are elements of high atomic weight; and, although the latter is formed by the disintegration of the former, it belongs in the calcium-barium group and is most closely related to barium in its chemical properties. Uranium belongs in the tungsten-molybdenum group. In their best-grade ores, radium and uranium occur in the ratio of 1 part radium to 3,200,000 parts uranium.

Mineralogy.—Radium was discovered in *uraninite* or pitchblende, a mineral that has no definite composition but is a mixture of the uranium oxides UO_3 and UO_2 and oxides of lead, calcium, bismuth, and numerous other elements. The other important source of uranium is *carnotite*, a potassium uranyl vanadate of approximately the following composition: $\text{K}_2\text{O} \cdot 2\text{UO}_3 \cdot \text{V}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$. It usually contains, also, traces of barium and calcium. Other uranium minerals are *autunite* and *torbernite*, but they are much less abundant.

Physical Properties of Uranium Minerals.—Carnotite is a bright canary-yellow mineral. It usually occurs as powdery aggregates or incrustations in sandstones. Uraninite has a pitchy luster on a freshly broken surface, hence the name "pitchblende." It is brown to black.

Mode of Occurrence of Uranium Ores.—Uraninite occurs in pegmatites, granites, and certain metalliferous veins that contain lead, silver, bismuth, and tin. Carnotite occurs in sandstones, either disseminated through them or aggregated into rich pockets. Some of these rich masses have replaced tree trunks in the deposits of the Colorado-Utah area. As a rule, carnotite ores are of low grade and must be concentrated.

Origin of Uranium Ores.—The uranium minerals that occur in pegmatites and metalliferous veins are evidently of magmatic origin. They are found associated with igneous rocks. The origin of carnotite deposits, especially of those in sands and sandstones, has not been satisfactorily explained. The source of the uranium and vanadium is difficult to

account for. These metals have evidently been introduced into the sedimentary rocks, but by what means is unknown.

Uranium Deposits. Domestic Deposits.—In the United States, which has produced about one-half of the world's total supply of radium, there are two important areas where uranium ores have been mined.

Uraninite occurs in metalliferous veins at Quartz Hill, near Central City, Gilpin County, *Colorado*. This deposit is one of the few of its kind in the world (others are in Czechoslovakia; Saxony; and Cornwall, England). The deposits are fissure veins that cut the pre-Cambrian metamorphic and igneous rocks as well as the Tertiary intrusives. The ores consist of *pitchblende*, pyrite, chalcopyrite, quartz, and some minor minerals. A later series of veins containing galena, sphalerite, chalcopyrite, and other minerals cuts the first set. These deposits have been a minor source of uranium and radium.

The *carnotite* deposits occurring over a wide area in *western Colorado* and *eastern Utah* are the chief source of uranium and radium in the United States. The ore occurs in the McElmo sandstone of Jurassic or Cretaceous age. The ores are irregularly distributed through the sandstone, and only the richer portions are mined. Most of the material is of a grade too low to be mined. The ore recovered at present (1928) is small in quantity but is high grade, as it runs from 4 to 8 per cent U_3O_8 . It must undergo considerable treatment for the recovery of the uranium or the radium.

Foreign Deposits.—Apparently the most extensive and richest uranium deposits known are those near Elisabethtown, Katanga, in the *Belgian Congo*. The ores are *pitchblende* and a series of alteration products. They occur in crumpled and faulted metamorphic rocks. The veins are very irregular in size and continuity. The extent of the deposits is unknown, but they are generally regarded as large.

The famous mines at Joachimsthal, Bohemia, now Jachymov, *Czechoslovakia*, still produce some uranium and radium. The *pitchblende* veins cut veins that contain a series of cobalt-nickel-arsenic minerals. Rich silver sulfides accompany the *pitchblende* and are of a later period of deposition. Radium was first discovered in *pitchblende* from these deposits.

Pitchblende occurs with cobalt-silver ores in *Saxony*, especially at Annaberg and Schneeberg, and it occurs in certain mines in the Cornwall tin district in southwestern *England*. Other countries where uranium ores are found are *Australia*, *South Africa*, *Russian Turkestan*, and *Madagascar*.

Uses of Uranium.—The chief value of uranium is as a source of radium. Uranium has been used in making steel alloys, and these alloys have an increased toughness, hardness, and other properties somewhat similar to those of tungsten steel. Their use is limited, however, because

of the high cost of uranium. Uranium has also been alloyed with aluminum. Probably its most common use is in giving yellow and brown tints to glazes on pottery and to glass. It is also employed in manufacturing iridescent glass and as a mordant in dyeing silk and wool. Certain uranium compounds are used in chemistry, photography, and medicines.

Uses of Radium.—The uses of radium are chiefly in the field of medicine. Much research work is being done to determine its value in treating certain diseases. It is the rays emitted from the radium that are made use of in treating disease.

The next most important use of radium is in the manufacture of luminous material for watch and clock dials, electric switches, pendants, and other objects. These luminous paints are mixtures of the radioactive salt and zinc sulfides. The zinc sulfide emits a flash of light when the rays from the radium hit particles of it. Radium salts are also used for experimental and scientific purposes.

Production.—Very little uranium-radium ore was produced in the world in 1927. The production in the United States was insignificant. The mines in the Belgian Congo, with their superior amounts of ore, dominate the world situation. Their large production caused the closing of the mines in the United States in 1926 and also the curtailment of their own production. The Belgian company possesses a large reserve of ore, but at \$70,000 per gram of radium, sales are slow. In 1928, the United States imported \$715,000 worth of uranium and radium salts.

An estimate of the world's total production of radium by countries is given in the following table:

TABLE 60.—ESTIMATED TOTAL WORLD PRODUCTION OF RADIIUM¹

Country	Amount, grams
United States.....	250
Belgian Congo.....	180
Czechoslovakia.....	42
Portugal.....	15
Madagascar.....	8
Russia (Ferghana).....	6
England (Cornwall).....	4
South Australia.....	1
Total.....	506

¹ *U. S. Mineral Resources*, 1926, Part 1, p. 263.

These 506 grams equal 1.11 pounds avoirdupois. Thus, about 1 pound of radium has been produced which, at \$70,000 a gram, would be worth \$31,752,000.

Selected Readings on Uranium and Radium

GALE, H. S.: Carnotite in Colorado, *U. S. Geol. Survey Bull.* 340, 1908.

HESS, F. L.: *U. S. Mineral Resources* for various years. All contain some material.

Bibliographies are given in most of the annual reports.

—: *U. S. Geol. Survey Bull.* 530, 1912.

MOORE, R. B.: Radium, *Am. Inst. Min. and Met. Eng. Trans.*, vol. LX, pp. 708-725, 1919.

PENROSE, R. A. F.: Spurr's "Political and Commercial Geology," pp. 201-208, McGraw-Hill Book Company, Inc., 1920.

ZIRCONIUM

Zirconium is a widely distributed element, especially in the acidic types of rocks. The estimated quantity in the earth's crust is 0.025 per cent.

Mineralogy.—Essentially all the zirconia, ZrO_2 , used comes from *zircon*, $ZrSiO_4$, and *baddeleyite*, ZrO_2 . Zircon is hard (hardness 7.5), heavy (specific gravity, 4.7), and insoluble. It is commonly brownish and opaque, but it may be transparent and of a red color suitable for gems. Baddeleyite also is fairly hard (hardness 6.5), has a higher specific gravity (5.5 to 6.0), and is insoluble. It is generally colorless but may be yellow or brown.

Mode of Occurrence.—Zircon is a common accessory constituent of acidic igneous rocks and pegmatites. All the zircon deposits worked are placers derived from the weathering of the original igneous rock and the subsequent mechanical concentration of the zircon. Baddeleyite occurs in pegmatites, from which placer deposits of the mineral are formed.

Origin of Zirconium Ores.—The common occurrence of zirconium in igneous rocks, where it has been one of the very first minerals to crystallize, shows its magmatic origin, as does also its occurrence in pegmatites. The subsequent concentration of the zirconium minerals into placers is a secondary weathering process.

Zirconium Deposits.—There are few important deposits of zirconium in the world. Formerly, a fair production of zircon was made from placers and residual materials in North Carolina, but the deposits of Pablo Beach in Duval and St. Johns counties, *Florida*, are now the only source of zirconium in the United States. The *zircon* of these deposits along with some other heavy minerals is recovered from beach sands. Zircon is found in numerous places in other parts of the United States but only in small quantities. The other important sources of zirconium minerals are the deposits of *Brazil* (chiefly *baddeleyite* from beach sands near Prado, Bahia) and southern *India* (Travancore).

Uses of Zirconium.—The extraordinary refractory properties of zirconia have led to its use in a great many refractory wares (see *Refractories*, p. 628).

The possibilities of the use of zirconia in ferro-alloys have been receiving considerable attention, with favorable results. Zirconia acts as a scavenger in the steel furnace, readily uniting with oxygen and nitrogen. About 1 per cent of the furnace charge, in the form of a ferro-

alloy containing about 20 per cent zirconium, is used for this purpose. Ferrozirconium (40 to 90 per cent zirconium) is malleable and ductile. Zirconium has also been successfully alloyed with aluminum. Cooperite is a nickel-zirconium alloy that is very hard and well suited for high-speed cutting tools. Zirconium steel is also said to make good armor plate and projectiles.

Zirconia has likewise been used as an insulator for heat and electricity and as an abrasive. A field of much promise is its use in giving opacity to paints, enamels, and lacquers. The hyacinth is a gem variety of zircon.

Production.—The United States produced 3,646 tons of zircon in 1927. The production figures for 1928 are not available, but about 430 tons of zirconium ores was imported that year for use in hardening steel.

Selected Readings on Zirconium

- LADDO, R. B.: "Non-Metallic Minerals," pp. 657-665, McGraw-Hill Book Company, Inc., New York, 1925. Contains a bibliography.
- MORRIS, H. C.: Zirconium, Spurr's "Political and Commercial Geology," pp. 209-215, McGraw-Hill Book Company, Inc., New York, 1920.

PART III
NON-METALLIC EARTH MATERIALS

CHAPTER XII

COAL

Coal is an amorphous substance consisting of various hydrocarbons. The word is derived from the Anglo-Saxon *col*, which means to blaze. It occurs in several languages of Gothic stock and is probably allied to the Latin *calere*, to be hot. Coal is gradually replacing wood as man's chief fuel, especially in the temperate zones. Even though it is dirtier than wood, it is preferred because of its greater heating power. When the steam engine was first invented, wood was used in it as fuel. Since coal was first introduced, its use has increased tremendously, until today (1928) the industries of all nations require an enormous coal tonnage. The coal production of the world was 1,470,000,000 metric tons in 1927.

History.—We have no evidence that coal was used by ancient man, and neither do we know the exact date of its first use. As early as 852 A.D., it was an article of household consumption among the Anglo-Saxons; in fact, it seems likely that coal was first used in England.¹ Branegan² reports that in America the Jesuit fathers found the Indians of the Susquehanna Valley burning coal in 1660. Father Hennepin, a French Jesuit missionary, records in his journal of 1679 the site of a "cole mine" on the Illinois River near Ottawa, Illinois. In 1701, coal was discovered near Richmond, Virginia, by the early settlers, and sporadic mining began in 1750. Anthracite was first produced about 1790.

Although coal was mined to some extent in Virginia, Pennsylvania, and Maryland throughout the early years of the nineteenth century, no production figures were kept before 1821. In 1822, the production in Virginia was 54,000 tons; in Pennsylvania, 4,500 tons. Since that time, coal production has increased rapidly, especially since 1880 (Fig. 124). Today (1928), the annual production in the United States exceeds 500,000,000 tons. The use of coal as a source of power, the world over, exceeds that of every other fuel, although this supremacy has been challenged in recent years by petroleum.

¹ Dr. Walter Hough of the U. S. National Museum is the authority for the statement that the Pueblo Indians of Arizona were the first people to use coal for fuel. He says they used it in firing pottery and that their use antedated by several centuries the use of coal elsewhere by civilized man.

² BRANEGAN, J. A., *Am. Mineralogist*, vol. XI, p. 166, 1926.

KINDS OF COAL

Three kinds of coal are widely known, but there are also intermediate varieties. No hard and fast lines divide the different classes; they grade

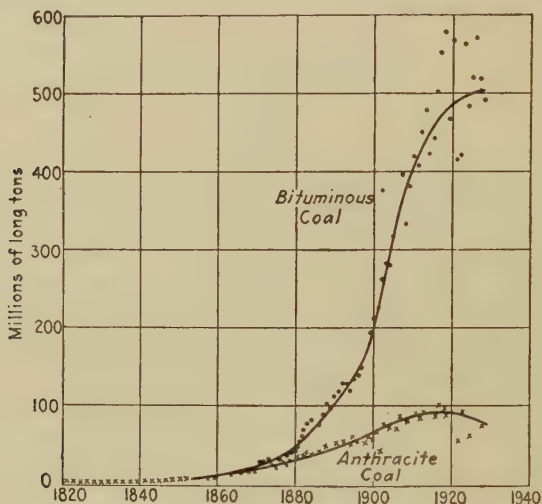


FIG. 124.—Production of bituminous and anthracite coal in the United States from 1820 to 1928. Curves represent the mean; dots and crosses, the yearly production. (Data from *U. S. Mineral Resources*, 1923, Part 2, pp. 549–550, and 1928, Part 2.)

into one another. The characteristics of the three common classes are easily learned, after which one is able to recognize them readily. They are:

- Peat.
- Lignite.**¹
- Subbituminous.
- Bituminous.**¹
- Semibituminous.
- Semianthracite.
- Anthracite.**¹
- Carbonite or natural coke.

Peat.—Peat consists of vegetable fibers (more or less decomposed) in an amorphous ground mass (Fig. 125 *a*). It may be spongy and light colored or dense and dark brown or black. In the bog, it contains about 90 per cent water. This must be reduced to 30 per cent before the peat can be used for fuel, and the ash content must not exceed 20 to 25 per cent. Peat burns with little smoke and if clean, *i.e.*, free from such impurities as mud, leaves but little ash. It gives off more heat than wood does.

Lignite.—Lignite is brown and possesses a distinctly woody (xyloid) or, less commonly, amorphous or canneloid texture (Fig. 125 *b*). Much

¹ Bituminous (soft coal), anthracite (hard coal), and lignite are the common coals.

of it shows small grains of resin. Lignite contains a high percentage of moisture (30 to 45 per cent). It averages 20 to 30 per cent volatile matter and about the same of fixed carbon (Fig. 126). The ash content ranges from 5 to 20 per cent and averages about 10. The sulfur content is relatively low. Lignite breaks up rapidly if exposed to the weather, due largely to the loss of the excessive moisture. Because of this fact, it cannot be hauled far from the mine. It is also apt to ignite spontaneously, hence must be stored carefully. It burns with a long, smoky, yellow flame and has a low heating power (average about 7,400 B. t. u.) (Fig. 126). It is used extensively in the manufacture of producer gas.

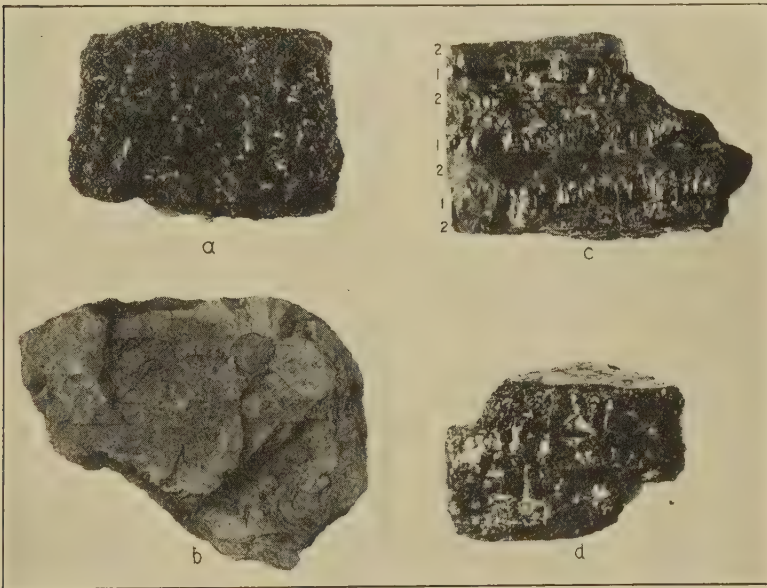


FIG. 125.—Illustrations of the four important kinds of coal. *a*, peat; *b*, lignite or brown coal; *c*, bituminous coal; *d*, anthracite; *c*-1, bands of glance coal; *c*-2, dull coal.

Subbituminous Coal.—Some subbituminous coal is called *black lignite*; and some, *amorphous coal* because of a dull, waxy luster. Subbituminous coal contains little woody texture; in fact, some kinds are canneloid, *i.e.*, consisting primarily of pollen and spores. Most subbituminous coals are banded (resembling bituminous); the exceptions are the canneloid varieties. The moisture content of subbituminous coal ranges from 10 to 30 per cent (Fig. 126), the volatile matter from 30 to 45 per cent, the fixed carbon from 35 to 45 per cent, and the ash from 3 to 25 per cent. Some varieties slack badly if exposed, due to loss of water. They are, therefore, difficult to ship yet are very good as fuel, being clean, capable of igniting easily, and having a calorific value ranging

from 8,000 to 10,000 B. t. u. If low in sulfur, subbituminous coal is good for manufacturing gas.

Bituminous Coal.—Bituminous coal (xyloid or woody coal) is commonly called “soft coal” to distinguish it from anthracite. It is black and is banded or laminated. Some of the layers have a brilliant luster



FIG. 126.—Diagrams showing the chemical composition and heat efficiency of the several ranks of coal. Upper diagram: Comparative heat value of the samples of coal represented in the lower diagram computed on the ash-free basis. Lower diagram: Variation in the fixed carbon, volatile matter, and moisture of coals of different ranks, from lignite to anthracite, computed on samples as received, on the ash-free basis. (U. S. Geol. Survey Prof. Paper 100-A, p. 8, 1917.)

(Fig. 125 c1) and others are dull (Fig. 123 c2). The bright layers are called *glance coal* (in England, *vitrain*) and the dull layers, *dull* or *mat coal* (in England, *durain*). Bituminous coal breaks into cubical or prismatic blocks and usually shows traces of vegetable remains. It ignites readily and burns with a long, smoky, yellow flame. The content of volatile

matter ranges from 42 per cent in low-ranking bituminous coals to 32 per cent in high-ranking coals (Fig. 126). The fixed carbon in the former is 47 per cent; in the latter, 65 per cent. The moisture content ranges from 11.5 to 3 per cent. Most bituminous coals are excellent gas coals. Any sulfur content is bad, making the coal less valuable for gas making or coking purposes. Coke is made from certain kinds of bituminous coal. Most cannel coals are varieties of bituminous coal having a high content of volatile matter. The heating power of bituminous coal ranges from 12,800 to 15,200 B. t. u.

Anthracite.—Anthracite is a jet-black, hard coal having a brilliant luster and a conchoidal fracture (Fig. 125 *d*). It ignites with difficulty and burns with a short, blue flame. It has a very low percentage of volatile matter (usually only 1 to 3 per cent) and a higher fixed-carbon content (95.6 per cent on the average) than any other coal. Its heating power is about 14,400 B. t. u. Anthracite represents the end of the change from vegetable matter to coal.

Carbonite or Natural Coke.—Carbonite or natural coke forms where igneous rocks cut across coal beds. The coal is hardened and rendered somewhat porous, although not so porous as artificial coke, because the volatile matter liberated cannot escape readily. Natural coke has been found in Utah, Colorado, New Mexico, and Virginia.

COMPOSITION OF COAL

Chemical Composition.—Coal is composed essentially of carbon, hydrogen, and oxygen. In addition, it always contains some ash and

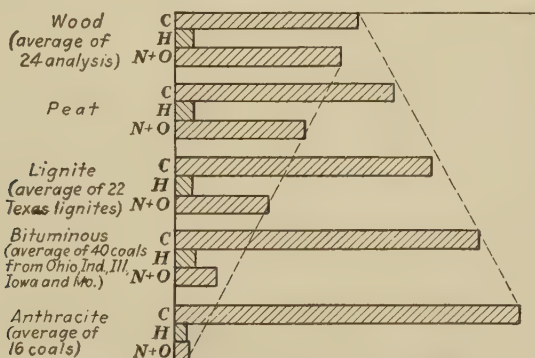


FIG. 127.—Composition of wood, peat, lignite, bituminous, and anthracite coal. Note uniform increase of fixed carbon from wood to anthracite, and an equally uniform decrease in the oxygen and nitrogen. Hydrogen content changes but slightly. (Data from Clarke, *Data of Geochemistry*, U. S. Geol. Survey Bull. 616, pp. 739, 742, 747, 752, 753.)

sulfur. The range in the carbon, hydrogen, and oxygen content for wood, peat, lignite, bituminous, and anthracite coal is shown in Fig. 127. The marked increase of carbon and decrease of oxygen is well shown by this diagram. The practice is, however, to determine certain compounds

TABLE 61.—SOME PROXIMATE ANALYSES OF THE COMMON COALS¹

Kind of coal	Location	Percentages					
		H ₂ O	Vo- latile mat- ter	Fix- ed car- bon	Ash	S	B. t. u.
(1) Anthracite.....	Mammoth bed, Schuyl- kill County, Pa.	2.80	1.16	88.21	7.83	0.89	13,298
(2) Semianthracite ² ...	Carbon Mountain, Ber- ing River field, Alaska	2.95	6.81	75.74	14.50	1.08	12,787
(3) Bituminous ³	Pittsburg bed, Con- nellsville, Fayette County, Pa.	2.82	29.97	59.84	7.37	1.22	13,991
(4) Subbituminous ⁴ ...	Louisville, Boulder County, Colo.	21.63	27.84	46.98	3.55	0.37	9,508
(5) Lignite ⁵	Glendive, Dawson County, Mont.	31.26	42.42	19.52	6.80	0.80	7,337

¹ U. S. Bur. Mines Bull. 22, Part 1: (1) p. 172; (2) p. 42; (3) p. 168; (4) p. 55; (5) p. 131.

² Tertiary.

³ Note high calorific value. Fine coking coal.

⁴ Cretaceous, Laramie formation.

⁵ Tertiary, Fort Union formation.

in the coal rather than the actual elements. These are *fixed carbon* (which denotes the fuel value), volatile matter, moisture, sulfur, and

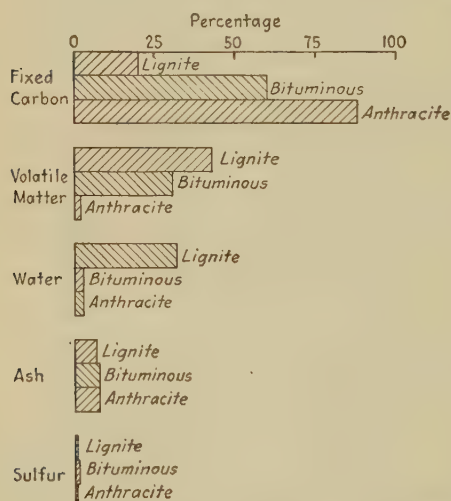


FIG. 128.—Variation diagram of proximate analyses of the different coals.

ash. Such an analysis is called a "proximate analysis." (Figure 126 shows the proximate composition of several coals and their heating value.) Some proximate analyses of the common coals, which illustrate the range in the composition, are given in Table 61.

Figure 128 shows graphically the variation in composition in the common coals.

Organic Composition.—

Microscopic study shows that the bodies of plants and trees, the twigs, leaves, bark, waxes, resins, spores, and pollen grains all enter into the formation of

coal. The relative amount of each material influences the final composition of the coal.

IMPURITIES IN COAL

Iron Sulfides.—The most common mineral impurity in coal is *pyrite* (erroneously called “sulfur” by the miners). The orthorhombic form of iron sulfide, *marcasite*, is generally present in some coal beds in considerable amounts. The pyrite occurs as veinlets, lenticular masses, balls, radiating forms (called “suns” by the miners), and disseminated grains. It may occur only on the bedding planes or may be within the beds or layers. The veins are commonly vertical. The *marcasite* is generally present as disseminated grains within the beds.

An excessive amount of these two iron sulfides is dangerous if the coal is stored in a wet, close place, as they (especially *marcasite*) will then decompose rapidly. The heat thus developed may ignite the coal or the wood of the confining structure. The iron sulfides are also bad because they are instrumental in forming clinkers in furnaces and because the sulfur produced from them is injurious. If the sulfur content exceeds 1.5 per cent, it renders the coal unfit for gas making and for coking. The air in cities and towns using coal containing iron sulfides is strongly impregnated with sulfur fumes on damp, quiet winter days.

Other Impurities.—*Calcite* and *gypsum* (called “scale” by the layman) are also common in coal. They occur principally along the joints; less commonly on the bedding planes. Relatively small quantities of *silica*, *kaolin*, *iron oxides*, and other substances are found in coal. All these substances go into the ash, or into the clinkers if the iron content is high. Rarely, *sphalerite* and *barite* are found in coal veins.

ORIGIN OF COAL

The view that coal is of vegetable origin is widely accepted and, also, that the several kinds of coal represent different degrees in the alteration of the original materials. The successive stages through which the vegetable material must pass are fairly easy to trace. The first step is well illustrated by the examination of present peat bogs.

PEAT BOGS

A peat bog or swamp consists of living plants at the top, a layer of dead plants next, and at the bottom a spongy, jelly-like mass. Each of these layers changes gradually into the next. The colloidal mass at the bottom is usually brown or black and contains plant remains which are more or less completely altered. Water containing different organic compounds, known as “humic derivatives,” constitutes a large portion of the mass. It is the water in a peat bog that prevents the vegetable material from rotting as it would do if exposed to the air. Submergence under water is therefore the absolutely essential initial condition, as it

brings about the preservation of the carbon contained in the vegetation and hence makes possible its later concentration into coal.

Conditions Necessary for Thick Accumulations of Peat.—Although peat beds 50 feet thick exist at present, such an amount would have been very inadequate in forming some of our thick coal beds. The total thickness of vegetable material necessary to form some existing coal beds would run into hundreds of feet. Field studies show, however, that broad, swampy, slowly sinking areas near sea level existed for long periods of time in the past. These conditions were ideal for thick accumulations of vegetable material. Pennsylvanian, late Cretaceous, and Tertiary times were periods when such conditions existed, and, moreover, plant life at those times was probably very luxuriant; hence, under these two sets of conditions the thickest of our coal beds could easily have been formed.

Flora of the Coal-forming Swamps.—The vegetation in these swamps consisted of the different plants that were growing during each geologic period. Over 3,000 species of plants have been described from the Pennsylvanian coal period. Ferns grew in abundance, and many of them were treelike plants. The Lycopods, which are mainly small shrubs today, grew abundantly and to a great size, some individuals attaining a height of 100 and a diameter of 3 feet. Rushes were common and also attained great heights, some being 90 feet high. Evergreens and numerous other forms grew at this time, but the majority of the plants in the Pennsylvanian period were spore bearing.

The flora of the Cretaceous age was remarkably like that of today, fully 90 per cent of the plants being similar to ours. Tertiary plants were essentially the same as those of today.

DEATH AND DECOMPOSITION OF THE VEGETATION

The coal-forming swamps, although near sea level, contained fresh water. As the vegetation in them died in the natural course of events, it was submerged. Occasional influxes of salt waters during the gradual subsidence of the land also caused the death of some fresh-water plants, which were likewise submerged.

The vegetable material (under water) then underwent changes which eliminated the moisture, oxygen, and part of the volatile matter, leaving a colloidal mass in which the carbon was concentrated. These changes were *chemical* and *biochemical* (later changes after swamp conditions ceased to exist were dynamochemical due to vertical and lateral pressure), and they were influenced by many factors, the important ones being the nature of the original material, the length of time it was acted upon, and the quality and depth of the swamp water. The biochemical changes constituted the action of bacteria upon the plant tissues; the chemical changes were produced by the action of solutions on the tissues.

The Biochemical Change.—The action of bacteria on the tissues was selective, certain parts having been more readily attacked than others. The elimination of the easily attacked tissues, such as protoplasm, starches, sap, and proteins, left the vascular parts which make up the xyloid coals. Various gases (CO , CO_2 , CH_4 , H_2O) were liberated, and the materials left were the waxy, resinous, and fatty substances, which in some places were sufficiently abundant to form boghead and cannel coal (two coals consisting mainly of such materials). The anaerobic bacteria functioned to considerable depths in the bog, possibly to 30 feet or more, where, due to the decrease in oxygen and increase in toxicity of the bog, they died out.

The Chemical Change. *Organic Acids.*—Chemical changes would certainly have been brought about by the organic acids developed in the bog or swamp. These acids aided in removing oxygen from the cellulosic material. According to Clarke,¹ Bornträger made analyses of peat and found from 30 to 60 per cent of humic substances.

Alkaline Sea Waters.—Important chemical changes were also brought about by the mingling of alkaline sea waters with those in the swamp. Little has been done in studying such reactions, because the swamp waters have been regarded as having been always fresh. They were, however, undoubtedly converted at times into brackish or slightly brackish waters by moderate influxes of sea water during storms or slight land subsidence. This mixture of waters would have had far-reaching chemical effects, some of which were probably the cause of the formation of mother-of-coal. This material is so different physically from the materials in other coals, that it must have undergone different chemical treatment. Since the sea water probably spread far through the swamps, this mode of origin would account for the widespread occurrence of mother-of-coal.

Taylor² suggests that the mingling of sea water with the swamp waters has markedly changed the character of the latter, even sufficiently to have overcome their toxic properties and thus furthered bacterial action as the waters freshened again.

PRODUCTS DUE TO THE CHEMICAL AND BIOCHEMICAL CHANGES

Due to original differences in the vegetable material and to the subsequent chemical and biochemical decomposition in the swamp, a two-fold division exists in coals: the *woody* or *xyloid coals* and the *spore* or *cannel coals*. There are intermediate varieties, however, as the two kinds grade into each other. The woody coals retain abundant evidence

¹ CLARKE, F. W., Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, p. 762.

² TAYLOR, MCKENZIE E., Base Exchange and the Formation of Coal, *Nature*, pp. 448, 449, Sept. 24, 1927.

(often wholly microscopic) of the original woody tissues, and the cannel coals are seen (always microscopically) to consist of spores, waxes, resins, and other resistant substances.

Woody Coal. *Glance or Bright Coal or Anthraxylon.*—Woody coal usually shows three distinct phases. The coal of the shiny layers, which has a conchoidal fracture, is called “glance” or “bright” coal (also “anthraxylon”). Glance coal consists largely of the vascular parts of the original wood, which were left after the removal by biochemical and chemical changes of the more easily destroyed portions: the protoplasm, sap, starches, proteins, and sugars. The woody structure has been preserved by certain chemical compounds formed by bacteria and possibly by chemical reactions. Some coals contain 80 per cent of this woody material.

Dull or Mat Coal.—Because of its lack of luster, the coal between the layers of glance coal is called “dull” or “mat” coal. The materials forming dull coal have undergone a greater degree of decomposition than those of the glance coal. The vascular portions of the wood have been largely destroyed, leaving only the very resistant parts, such as cuticles, horny seed coats, and spores. The dull coal produces most of the ash, as it contains not only the hard parts just mentioned but also any inorganic material that has been washed or blown into the swamp.

Mineral Charcoal, Fusian, or Mother-of-coal.—The third substance of woody coal (best seen on the bedding planes) is called “mineral charcoal,” “fusian,” or “mother-of-coal.” This material, as one name implies, is charcoal. David White regards it as having been the product of exposure to air of the decaying woody material, together with the concentration by evaporation of a humic derivative produced by bacterial decay, the humic compound having soaked into the wood and prevented further decay when resubmergence took place. As already suggested in the discussion of chemical changes, there is a strong possibility that this coal is due to strictly chemical reactions. Another view is that mother-of-coal was caused by forest fires sweeping over the swamp.

Jet.—Jet is a variety of woody coal formed from large portions of trees which had become highly saturated with the humic material. Due to its hardness and brilliant luster, jet is polished and extensively used for ornaments.

Spore Coals.—The spore coals were formed in open spaces in the swamp, where any woody material would generally have been entirely decomposed. Spore coal consists of wind-borne spore and pollen grains, varying amounts of undecomposed resins and waxes, some algal matter, and rarely traces of animal organisms. The coal is massive and breaks with a marked conchoidal fracture. Some varieties contain such a large amount of volatile hydrocarbons that the coal can be ignited with a match. Spore coals are excellent gas producers.

BURIAL AND SUBSEQUENT CHANGES

Burial.—The biochemical and chemical processes (which formed the initial coals) took place in the living swamp, which in order to permit a thick accumulation of vegetation must have been subsiding at a rate just rapid enough to maintain a zone of growing plants at the top. Rapid subsidence would have submerged the vegetation and killed it, as is proved by swamps buried beneath the sea along the Carolina coast. Following complete submergence, sediments would have been washed over the peaty accumulation, have buried it, and retarded or stopped any further biochemical or chemical changes. At the time of burial, the peaty material contained large amounts of water (according to White, 80 to 90 per cent near the top of a deposit), which were largely eliminated during the consolidation that followed the deposition of sediments upon it.

Dynamochemical Changes.—Subsequent changes through which the peaty material passed to become lignite, subbituminous, bituminous, semianthracite, anthracite, and finally graphite were all *dynamochemical*. The dominant factor in these changes was *pressure: vertical pressure* due to the weight of sediments deposited over the organic material (the so-called "law of Hilt") and *lateral pressure* (the "thrust stresses" of White) due to compressive forces in the outer part of the earth's crust.

Vertical Pressure.—As long ago as 1873, Hilt had pointed out that the fixed-carbon content of coal increased downward. He had deduced that this was because the coal was buried under a great load of sediments. His deduction was logical, for compaction and change take place in the associated sediments under the same conditions. The field evidence as directly applied to coal is meager, however, because there are few localities in which more than one bed is mined from the same shaft. Reeves,¹ in an excellent paper, has strongly supported Hilt's law as an explanation of the formation of the higher grades of coal.

Certainly, we are unjustified in not recognizing the significance of vertical pressure in coal formation. It seems so unlikely, for instance, that the bituminous coal of such regions as those in Indiana, Illinois, Iowa, Kansas, and Missouri was formed by lateral rather than vertical pressure.

Jones² thinks that coal formation may have been influenced subsequently by circulating ground waters as well as by original composition differences of the source materials.

Lateral Pressure.—David White thinks that lateral pressure was a much more important factor in producing the higher grades of coal

¹ REEVES, FRANK, The Carbon-ratio Theory in the Light of Hilt's Law, A. A. P. G., Bull., vol. XII, pp. 795-824, 1928.

² JONES, I. W., Carbon Ratios and Index of Oil and Gas, *Econ. Geol.*, vol. XXIII, pp. 353-380, 1928.

than vertical pressure. He has collected evidence bearing upon this from all parts of the United States, of which the following instances are examples.

Between Pittsburgh and Windber, Pennsylvania, 70 miles east, the fixed-carbon content of coals increases from 60 to 83 per cent. Folding in the beds at Windber is much more marked than at Pittsburgh. Farther east in the Lehigh area of the anthracite field, where the folding is intense, the carbon content reaches 97 per cent. The Lehigh area is nearer the source of the thrust than Pittsburgh, a fact substantiating White's view that coal always has the highest carbon content where nearest the source of the thrust. The Pittsburgh bed gains 22 per cent in carbon between Clarksburg, West Virginia, and Cumberland, Maryland.

In the coal fields of the Rocky Mountain area, wherever a bed extends from the plains to one of the numerous mountain ranges to the west, it is highest in fixed carbon where nearest the range. The brown lignite of the Fort Union (Lower Eocene) at Wilton, North Dakota, has become a black subbituminous coal at Miles City, Montana, 240 miles west; and, 150 miles farther west at Red Lodge, Montana, it has reached the stage of bituminous coal. A still more remarkable change occurs in Eocene coals in the Chihalis region of western Washington, where a semilignitic coal having a fixed-carbon content of 45 per cent reaches 80 per cent in the foothills of the Cascades 30 to 40 miles distant. The dynamochemical changes produced numerous gases, which, if the higher coals were to be formed, had to escape. A means for this was furnished by the fissures which were developed in the overlying rocks during the folding.

The Relative Importance of Vertical and Lateral Pressure in Coal Formation.—There is no doubting the significance of thrust stresses in producing higher grades of coal in folded areas, but far from folded areas (as in the states already mentioned, and other regions could have been cited), where the beds at most are only gently dipping, there is no evidence to support the view that the coal was developed by lateral pressure. Many coals in such areas are similar to those in folded areas, and their formation must have been due to other factors, among which vertical pressure was certainly the most important.

Heat a Minor Cause in Forming Coal.—Although heat was doubtless an aid in the formation of higher grades of coal, it was probably never present in sufficient amounts to be an important factor. Where igneous rocks have cut coal beds, the adjacent coal has been changed to natural coke. The change does not extend far from a dike, however; usually only 15 to 20 inches from its edge, though rarely to a distance of 15 feet.

A sill is more effective than a dike and may convert a bed of coal into anthracite either above or below it, though the effect is generally

greater above. In the Yampa coal field of western Colorado, a sill 75 feet thick developed anthracite in a bed 45 feet above it, semianthracite 55 feet above, and the coal was affected as far as 80 feet above. A 200-foot sill will convert a bed of coal into a good anthracite to a depth of 26 feet and into a semianthracite to a depth of 44 feet. These changes are probably due mainly to vapors emanating from the sill rather than to heat. Natural coke has a much lower porosity than artificial coke, 10 to 25 per cent being an average for the former, and 45 per cent for the latter. (See Table 69, p. 376 for the composition of both kinds of coke.)

RESULTS OF THE VARIOUS PROCESSES

During the changes from the original wood to the final anthracite, there has been a constant loss of oxygen and, to a lesser extent, of hydrogen (Fig. 127, p. 343). Although not shown in the diagram, there has actually been a slight loss of carbon: in methane, CH_4 , carbon monoxide, CO , and carbon dioxide, CO_2 . The heating power of coal has increased as the oxygen decreased; in fact, White has shown that an excess of oxygen in coal is as objectionable as an excess of ash.

The chemical change has been accompanied by physical changes, such as an increase in hardness of the coal, a decrease in volume, and the development of numerous joints. Although greatly compressed, the vegetable material, even in anthracite, has retained many of its original characteristics. The wood cells were flattened and distorted but are recognizable.

It is truly remarkable that the different processes of coal formation when applied to vegetable accumulations under all sorts of climate in widely separated areas and under a wide range of other physical conditions should produce coals so remarkably alike, but such is the case.

SUMMARY

Coal has been formed from vegetable accumulations under water in swamps that were near sea level. The initial stage in coal formation was the breaking up of the plant tissues by bacterial action (biochemical change) and by different organic and inorganic solutions (chemical change). Hydrogen, nitrogen, oxygen, and some carbon were eliminated in the processes. Most of the carbon, however, was concentrated into a colloidal mass which underwent further changes (dynamochemical) induced by pressure, which was, in part, vertical (due to burial) and, in part, lateral (due to folding). The dynamochemical changes completely carbonized the mass and converted it into the various coals. These processes gave rise to remarkably similar coals under widely varying conditions in all parts of the world.

RATE OF ACCUMULATION OF COAL

It is of interest to speculate (for speculation it is) concerning the rate at which coal was formed. The rate depends upon the nature of the vegetation, the luxuriance of its growth, and the amount of it preserved.

Ashley¹ estimates that 1 foot of peat will accumulate in 10 years and that this foot will become $1\frac{1}{8}$ inches, or even less, due to loss of volatile constituents and to compression. He further estimates that 3 to $3\frac{1}{2}$ feet of compressed peat would equal 1 foot of coal. According to these figures, 1 foot of compacted peat would accumulate in about 100 years, and therefore 1 foot of coal would form in about 300 years.

Some of our remarkably thick veins would thus have required a very long period of time for accumulation. A subbituminous vein at Adaville, Uinta County, Wyoming, has a thickness of 84 feet, broken only by a 2-inch clay parting.² Twenty-four thousand years would have been required for its formation if the above rate held.

MODE OF OCCURRENCE OF COAL

As coal is a sedimentary rock, it occurs interstratified with other sedimentary rocks, such as shale, sandstone, and limestone. Any



FIG. 129.—Exposure of a thick bed of lignite in the Fort Berthold Indian Reservation, North Dakota. (Drawn from a photograph by Bauer and Herald, *U. S. Geol. Survey Bull.* 726, pl. 13-B.)

sedimentary rock may act as a cover for a coal bed or may, of course, underlie it, but shale is the most common one in either place (Figs. 129 and 130). Shales differ greatly in strength. Some are strong enough to form a good roof after the coal has been mined, and others are so weak

¹ ASHLEY, G. H., *The Maximum Rate of Deposition of Coal*, *Econ. Geol.*, vol. II, pp. 34-47, 1907.

² *U. S. Geol. Survey Bull.* 285, p. 338.

that the roof must be propped up as soon as the coal is removed. Rarely, clay (in some deposits, fire clay, Fig. 130) underlies coal, and it may contain fossil roots of the swamp plants which had grown down into it. Less commonly, the upright trunks of trees are found extending from these roots directly up into the coal bed. These facts prove that the coal was formed in place.

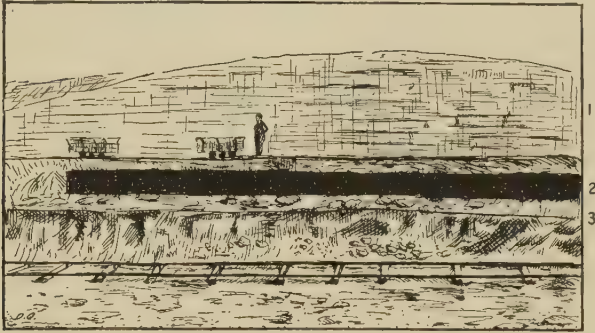


FIG. 130.—Clay pit at Oskaloosa, Barton County, Missouri, showing fire clay (3), coal (2), and shale (1). Fire clay is 5 feet thick; coal about 31 inches; shale, 16 feet. (After photograph by Hinds, *Missouri Geol. Survey*, vol. XI, pl. 4, p. 67.)

Coal is rarely exposed at the surface, because it weathers rapidly to a black earthy material called by the miners *coal blossom* or *smut* (Fig. 131 A). Where erosion along a stream is rapid, however, the beds may be well exposed (Fig. 129).

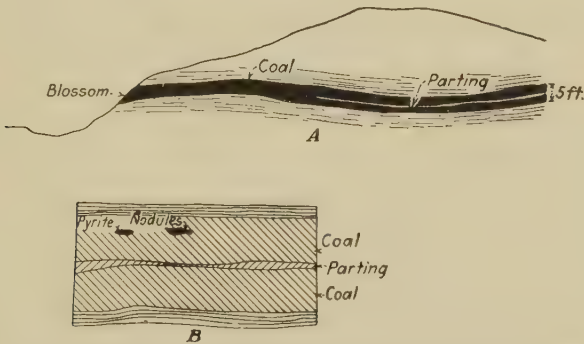


FIG. 131.—A, coal bed showing blossom and a parting. B, showing in detail the coal bed and its parting, and pyrite nodules in the coal.

Thickness of Coal Beds.—Coal beds (also called “veins” and “seams”) range in thickness from that of a sheet of paper to 100 feet. The 84-foot bed at Adaville, Wyoming, is the thickest vein in the United States. Cannel coal of remarkable thickness occurs in sinkhole deposits in Cooper and Moniteau counties, Missouri. These deposits, of Pennsylvanian age, cover only a small area, but several contain 55 to 65 feet of cannel

coal. In one sinkhole, 24 feet of bituminous coal lay above 30 feet of cannel coal. The Mammoth bed in the Pennsylvania anthracite region has a thickness of 50 to 60 feet.

The following table is of interest because it shows that the beds of medium thickness are not only the most common but also are the most extensively mined. Although those less than 3 feet in thickness produced only 3.8 per cent of the total production in 1917, the total tonnage from them amounted to 20,000,000. Very few coal beds less than 2 feet thick are mined in the United States.

TABLE 62.—PERCENTAGE OUTPUT OF COAL BEDS OF VARIOUS THICKNESSES IN THE UNITED STATES, 1917¹

Thickness of beds, feet	Percentage output
Under 2	0.6
2 to 3	3.2
3 to 4	13.3
4 to 5	17.6
5 to 6	19.9
6 to 7	13.8
7 to 8	9.9
8 to 9	5.3
9 to 10	5.6
10 to 12	2.0
20 or more.	0.3
Thickness not reported	8.5
	<u>100.0</u>

¹ U. S. Geol. Survey *Press Bull.* 428, October, 1919.

The thickness of coal beds is usually not uniform, very few having the remarkable persistence of the Pittsburgh bed in Pennsylvania, Ohio,



FIG. 132.—The distribution of the Pittsburgh coal bed in Pennsylvania, Ohio, and West Virginia. Dotted line shows possible former extent. (Data from various publications.)

and West Virginia, which averages 7 feet in thickness over an area of 2,100 square miles (Fig. 132). Lateral variations in thickness are usually

common, a difference of several inches occurring in some beds within 100 feet.

Number of Beds to an Area.—In the United States, the number of beds in any given area ranges from 1 to over 100. The Puget formation (Eocene) in Washington contains about 125 coal beds. These range from 1 to 60 feet in thickness.¹ According to David White, this formation is about 10,000 feet thick, but most of the coal occurs in the lower 3,000 feet where the beds are mainly of fresh-water origin. A single bed of coal is rarely found in a coal-bearing series in any region. The following table gives the number of coal beds in each of the eastern states producing bituminous coal in 1918:

TABLE 63.—NUMBER OF COAL-PRODUCING BEDS IN THE EASTERN STATES, 1918

States	Number of beds	Number of beds producing maximum percentage of coal
Alabama.....	42	4 beds produced 62.51 per cent
Arkansas.....	7	1 bed produced 80 per cent
Illinois.....	9	2 beds produced 90.54 per cent
Indiana.....	7	2 beds produced 81 per cent
Iowa.....	24	Production widely scattered
Kansas.....	6	2 beds produced 63.22 per cent
Kentucky.....	82	Names may overlap. Production scattered
Maryland.....	18	2 beds produced 36 per cent
Missouri.....	24	2 beds produced 34 per cent
Ohio.....	15	3 beds produced 83 per cent
Oklahoma.....	16	3 beds important
Pennsylvania.....	26	The Pittsburgh produced 53 per cent
Tennessee.....	33	Production scattered
Virginia.....	35	Production scattered
West Virginia.....	88	Production scattered

¹ U. S. Mineral Resources, 1918, Part 1, pp. 1380-1388.

STRUCTURAL FEATURES OF COAL

Partings.—A coal bed may be separated into two or more parts by thin beds of shale, slate, bone, or more rarely narrow bands of pyrite (Fig. 131 A and B). These partings interfere in mining if the coal seams are too thin to be mined separately. Where the parting is very thick, it is called a *split*. What coal miners call *clay slips* are common in some coal areas (Figs. 133 and 134). The slip is a mass of clay of varying width cutting part way, or entirely, across a coal bed. This mass is usually forced up into the coal from the underlying bed, especially where the coal has been broken during consolidation. Clay slips are actually clastic dikes. Local elongated protuberances of the clay floor or downward bulges from the roof that cut partly across the coal bed are

¹ CHAMBERLIN and SALISBURY, "Geology," vol. III, pp. 202, 203, 1906.

known as *rolls*, *cut outs*, or *horsebacks* (see Fig. 134). All these features interfere more or less in mining the coal.

Slickensides.—In some localities, the clay underlying a coal bed shows striated surfaces called *slickensides*. These features are caused by movements of the coal during consolidation. Slickensides lie in every

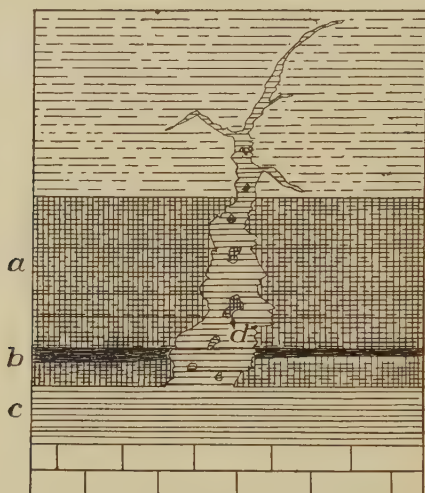


FIG. 133.—Clay slip (or elastic dike) cutting entirely through a coal bed and entering the overlying shale. The clay below the coal was forced up through it into the shale.

possible position. Many occur several feet below the coal, though usually they are immediately below it. Slickensiding generally takes place if rocks underneath the clay are uneven and resistant. It is especially apt to occur if a hard limestone or sandstone lies immediately below the clay.

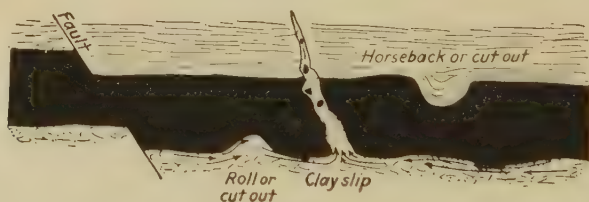


FIG. 134.—Clay slip, horseback or cut out, roll, and fault in a coal bed.

Faults.—Faults are fairly common in coal. Some have a displacement of an inch or less, some of many feet (Fig. 134). Large displacements necessitate mining at different levels. A striking feature of the small faults in the coal in Missouri is their highly polished slickensided surfaces. They have been developed by less than an inch of displacement.

GEOLOGICAL DISTRIBUTION OF COAL IN THE UNITED STATES

Coal is found in the United States in a wide range of rocks: from those of Carboniferous age (Mississippian, Pennsylvanian, and Permian,

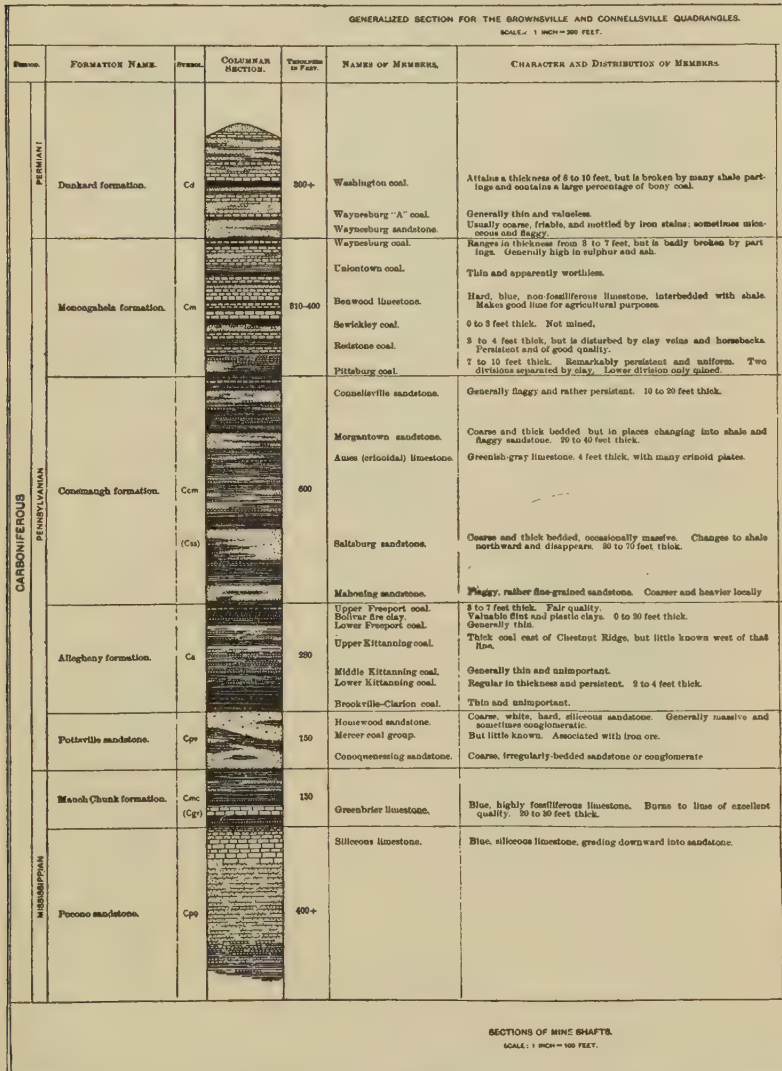


FIG. 135.—Distribution of the coal in the Carboniferous in the Brownsville-Connellsville area, Pennsylvania. (*U. S. Geol. Survey Folio 94.*)

see Fig. 135) to those of the Pleistocene period. Its occurrence is most widespread, and it is best developed in Carboniferous rocks; in fact, the era was so named on account of the abundance of coal in the rocks of the

period. The Cretaceous (Fig. 136) and Tertiary (Fig. 137) (the Triassic has a little coal) were the other important coal-forming periods. In the United States, the coal of these periods is roughly distributed thus:

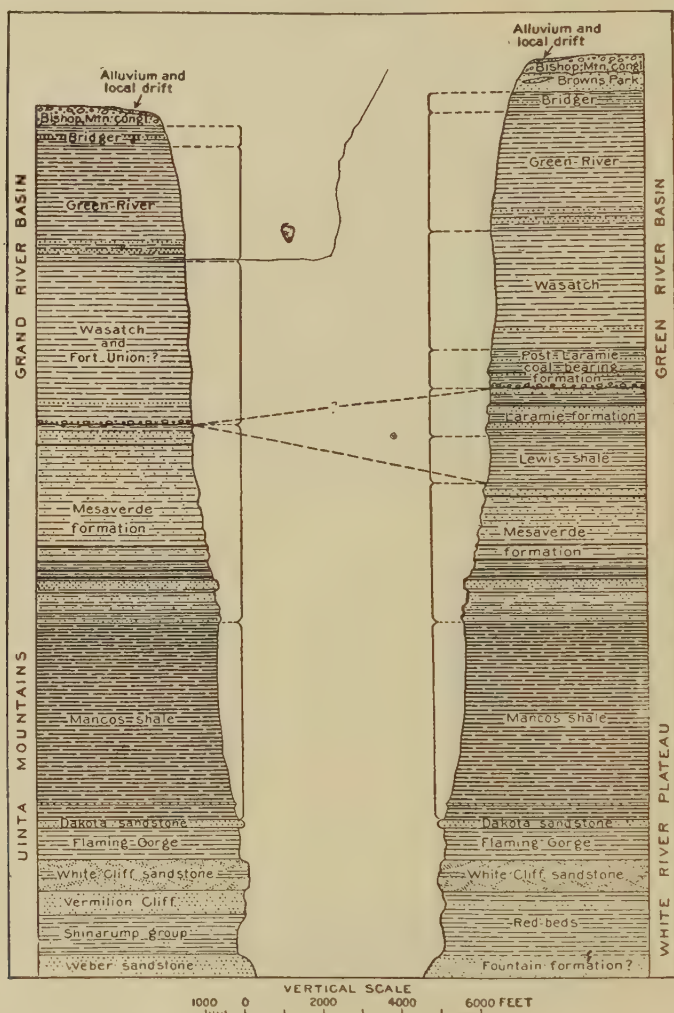


FIG. 136.—Generalized stratigraphic sections of Grand River Basin (Uinta Mountains) and Green River Basin (Rocky Mountains foothills). Shows the distribution of coal (black beds) in the Mesa Verde and Laramie (Cretaceous) and the Post-Laramie (Tertiary) formations. (*U. S. Geol. Survey Bull.* 415, p. 42, 1910.)

Carboniferous coal, east of the hundredth meridian; Cretaceous and Tertiary, west of the hundredth meridian (save for the Tertiary coals in the Gulf region).

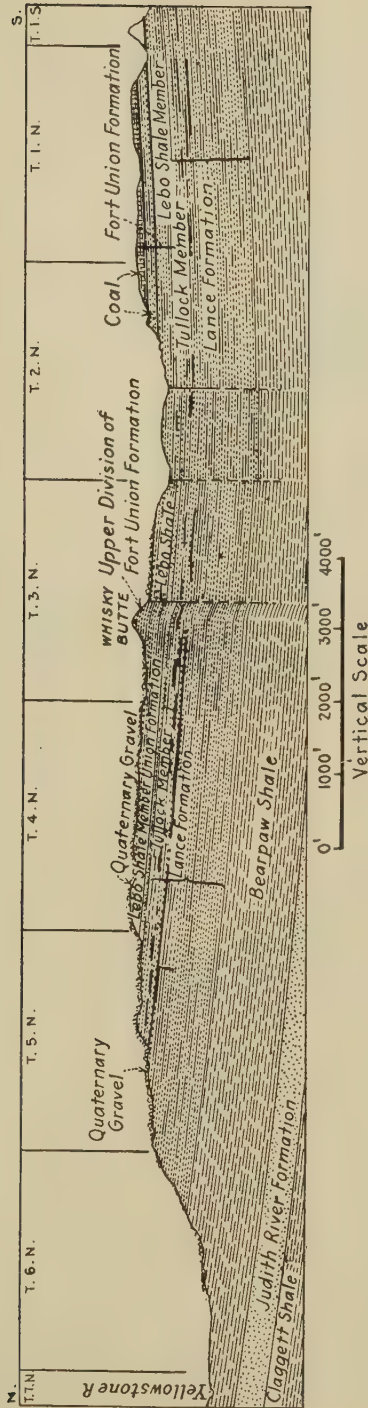


FIG. 137.—Generalized profile and structure section from Hysham south along divide between Sarpy and Tullock creeks to south edge of Tullock Creek field, Montana. Shows distribution of coal (black) in Lance and Fort Union formations of the Tertiary. (*U. S. Geol. Survey Bull.* 749, p. 6, 1923.)

may be found in the different state and U. S. Geological Survey reports. Each valuable coal bed has a name or number; and, as the beds cannot be accurately correlated in different fields, each area has its own particular set of names. These names and the minor details of the beds and associated rocks are unessential to the student seeking a general knowledge of coal. A long working acquaintance with the different coal fields would be required to become thoroughly familiar with each bed.

The chief fields, their approximate areas, and the age of the coal are given in the following table:

TABLE 64.—GEOLOGICAL AGE AND AREA OF THE CHIEF COAL FIELDS OF THE UNITED STATES¹

Field	Geological age	Area, square miles
Appalachian.....	Pennsylvanian	70,000
Eastern Interior.....	Pennsylvanian	47,000
Western Interior.....	Pennsylvanian	75,000
Northern Interior.....	Pennsylvanian	11,000
Rocky Mountain.....	Cretaceous and Tertiary	126,000
Gulf Coast Lignite.....	Tertiary	2,100
Pacific Coast.....	Tertiary	1,900

¹ Compiled from Table 67, p. 368.

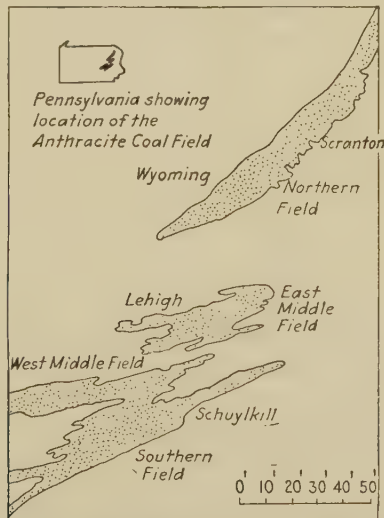


FIG. 139.—Anthracite coal fields of Pennsylvania.

The Appalachian Field.—The Appalachian field supplies over 70 per cent of the bituminous coal of the United States and all of the anthracite.

It extends from Pennsylvania to Alabama and from eastern Pennsylvania, where the anthracite field lies, to Ohio. Pennsylvania coal is uniformly of a very high grade.

Anthracite.—The anthracite coal comes from a limited area of 480 square miles in Pennsylvania (Fig. 139). There are three important districts: the Wyoming, producing (1925) 55.2 per cent of the total;

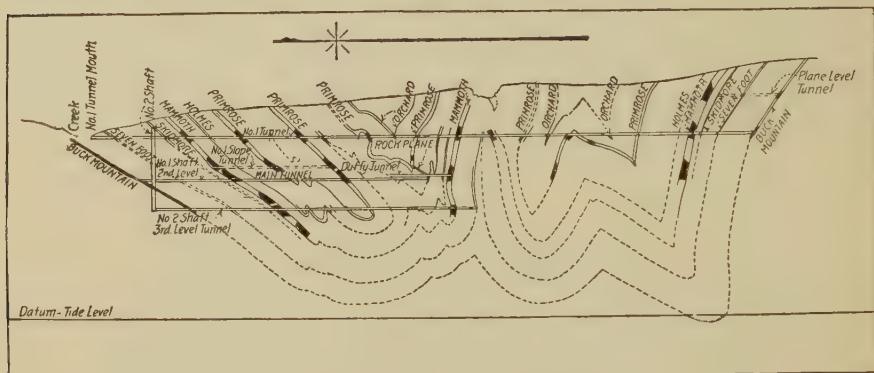


FIG. 140.—Folding in rocks of the anthracite area in Pennsylvania. (*J. F. Kemp, Trans. Am. Inst. Min. and Met. Eng.*, vol. LXVI, p. 314, 1921.)

the Schuylkill, producing 30.4 per cent; and the Lehigh, 13.9 per cent. A small area in Sullivan County produces less than 1 per cent. The rocks in the anthracite area have been strongly folded (Fig. 140). Only a small part of the coal originally there is left; most of it has been removed by erosion.

Bituminous Coal.—The eastern part of the bituminous region in the northern Appalachian area is more intensely folded than that to the west

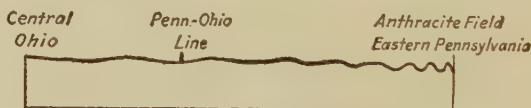


FIG. 141.—Diagrammatic sketch of folding in the Appalachian coal field.

(Fig. 141). The Allegheny and Monongahela formations (Fig. 135) of Pennsylvanian age produce most of the coal in the northern Appalachian field. Many beds of high-grade coking coal occur in the Appalachian field; the Pocahontas, Pittsburgh, and Hocking Valley coals are especially suited for this purpose. The Pottsville formation (Pennsylvanian) produces most of the coal in the southern Appalachian area. The Appalachian field furnishes the coal for the eastern industrial centers, as well as the coke for a large part of the United States. The area near Connellsville, Pennsylvania, is especially famous for its coke-producing coal.

Eastern Interior Field.—The Eastern Interior field lies in Illinois, Kentucky, and Indiana. It is basin shaped, and the coal is being mined in the shallower parts around the margin of the basin. These areas are in northern and southwestern Illinois, western Indiana, and Kentucky. Several excellent grades of coal are produced from beds ranging from 2 to 7 feet in thickness. The annual production of this area ranks next in amount to that of the Appalachian field, largely because it is favorably located to furnish coal to Chicago, St. Louis, and other large cities in the Mississippi Valley.

Western Interior Field.—The Western Interior field includes Iowa, Kansas, Missouri, Oklahoma, and Arkansas (named in the order of their importance). The coal of this field is of a lower grade (due largely to the presence of impurities, rather than to a lower heating value) than that of the eastern fields and hence is forced to find its market within a fairly short haul of the mines. The coal-bearing formation is essentially flat over the entire region, save for locally folded areas in Oklahoma and western Arkansas. The locality in Arkansas produces some semianthracite. The *Southwestern field* in Texas is a continuation of the Western Interior field.

The Northern Interior Field.—The Northern Interior field lies in the southern peninsula of Michigan. The coal occurs in a shallow basin. It is of low grade and consequently is used locally.

The Rocky Mountain Field.—The Rocky Mountain field includes the following states (in the order of their importance): Colorado, Wyoming, Utah, New Mexico, Montana, North Dakota, and South Dakota. The coal of this field ranges from lignite to anthracite, though bituminous and subbituminous are the most important. The anthracite is of very little importance. It occurs in Colorado, Utah, and New Mexico and is due to igneous and, to a lesser extent, regional metamorphism. The Rocky Mountain field contains a tremendous tonnage of coal, but as yet it has been developed only at points near a ready market or where the coal is of excellent grade. In time, it will be one of the great producing areas of the United States.

Colorado is the leading producer in the Rocky Mountain field, furnishing yearly about 10,000,000 tons of the total annual 28,000,000 tons produced by the entire field. The most important region in Colorado is the Trinidad-Walsenburg area (Los Animas and Huerfano counties in southeastern Colorado). A large amount of coke is produced in that region. Other important coal areas in Colorado are in Weld, Fremont (Cañon City), Boulder, Gunnison, and Routt counties.

The coal in Wyoming comes mainly from two southwestern counties: Sweetwater County, in which the Rock Springs field is located; and Lincoln County, where the Kemmerer field is located. Sheridan County in the northern part of the state also produces considerable coal.

The most important coal field in Utah is in Carbon County in the eastern part of the state. Over 95 per cent of the state's production comes from that county. The coal occurs in thick beds, a fact which favors a large production. Considerable coke is made in Utah.

The coal fields of New Mexico are mainly in Colfax and McKinley counties. Colfax County is adjacent to the Trinidad, Colorado, field, and McKinley County is in the western part of the state. A large tonnage of coke is produced annually in New Mexico.

Lignite is the only coal mined in North and South Dakota. Of the million and a half tons mined annually in the two states, South Dakota produces only about 12,000 tons. North Dakota's production comes from the counties in the western part of the state.

Pacific Coast Field.—The Pacific Coast coals are of little importance save in the state of Washington, which produces about 2,500,000 tons annually. The coal, which is lignite, subbituminous, and bituminous, is of higher grade near the mountains where folding has been intense. There has been considerable disturbance of the coal beds in some of the fields. The important mining regions of the state are the Roselyn field on the east side of the Cascades and the Ring and Pierre County fields around the southeastern end of Puget Sound. Alaska has some good coal, but the areas are scattered and not well developed. The production in 1928 was only 126,000 tons.

Gulf Coast Lignite Field.—There are considerable areas where lignite occurs in Texas and Louisiana, but only the deposits in Texas are worked. That state produced 1,169,000 tons in 1927.

Peat Fields.—The United States has about 11,000 square miles of peat bogs, estimated to contain 12,000,000,000 tons of peat. Of these areas, Minnesota contains nearly half, and the other northern states to the east contain most of the remainder. As yet, there is no well-developed market for peat in the United States. Less than 100,000 tons are produced annually. In Europe, about 15,000,000 to 20,000,000 tons of peat is used each year.

MINING OF COAL IN THE UNITED STATES

The total number of mines that produce bituminous coal is astonishing. The figures collected by the U. S. Geological Survey in 1922 (used in Table 65 because figures for later years do not include the smaller mines) showed that there were over 14,000 bituminous mines (including wagon mines).

Number of Miners and Their Daily Production.—Nearly 759,000 men were engaged in coal mining in the United States in 1927. Of these, 84 per cent was employed underground. The anthracite miners produced, per man, 2.15 tons daily in 1927; and the bituminous miners, an average of 4.55 tons per day. Anthracite is more difficult to mine than

TABLE 65.—BITUMINOUS COAL MINES IN THE UNITED STATES, 1922¹

Rank according to size	Number of mines	Percentage of total number of mines	Total production, net tons	Average production per mine, net tons	Percentage annual production
Class 1.....	416	2.9	131,876,000	317,010	31.2
Class 2.....	848	6.0	117,195,000	138,202	27.8
Class 3.....	1,084	7.7	77,287,000	71,298	18.3
Class 4.....	3,139	22.1	77,203,000	24,595	18.3
Class 5.....	8,663	61.3	18,707,000	2,159	4.4
Total.....	14,150	100.0	422,268,000	29,842	100.0

¹ U. S. Mineral Resources, 1922, Part 2, pp. 533, 534.

bituminous coal. In bituminous mining, the amount produced per man has been increased by 70 per cent through the use of machines.

Methods of Mining Bituminous Coal.—The arrangement of the mine in bituminous mining may be either the *room-and-pillar system*

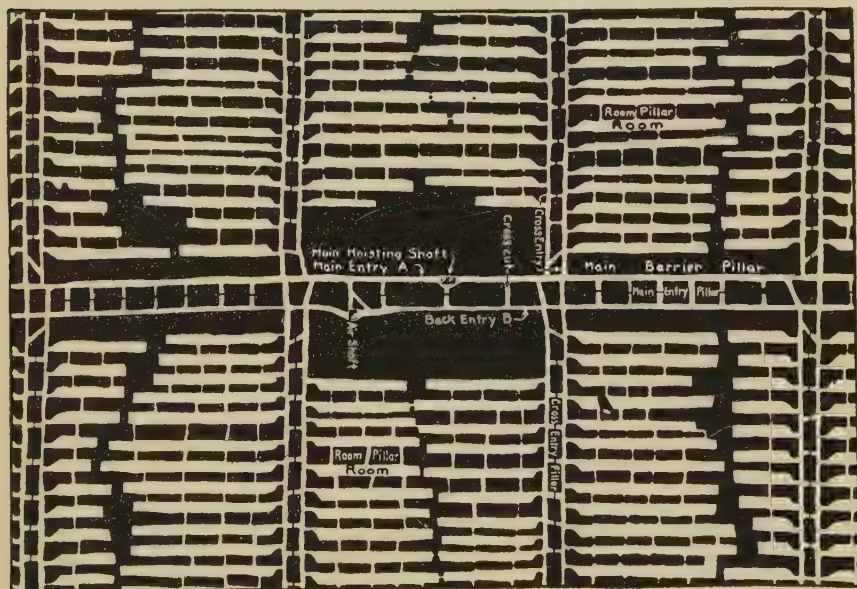


FIG. 142.—Plan of a room-and-pillar mine. White areas represent rooms; and black, coal. Note how nearly half the coal is left to support the top. (After Bement, Ill. Geol. Survey Bull. 56, Fig. 17, p. 47.)

(Fig. 142), in which the coal is mined from the rooms and the pillars are left as supports; or the *long-wall system* (Fig. 143), in which all the coal is removed as mining proceeds and the roof allowed to settle. The methods of mining vary. The coal may be drilled and broken down by

powder (8.7 per cent was thus produced in 1927); it may be broken down after being undercut, either by hand (15.1 per cent) or by machine (72.2 per cent); and some is produced from strip pits.

Losses in Bituminous Mining.—The loss in mining bituminous coal is estimated as $\frac{1}{2}$ ton for every ton mined. The losses are greatest where the room-and-pillar system is used in connection with shooting from the solid, the loss then exceeding the figures given above—in fact, closely approaching ton for ton. Losses are greater, as a rule, in small mines than in large ones.

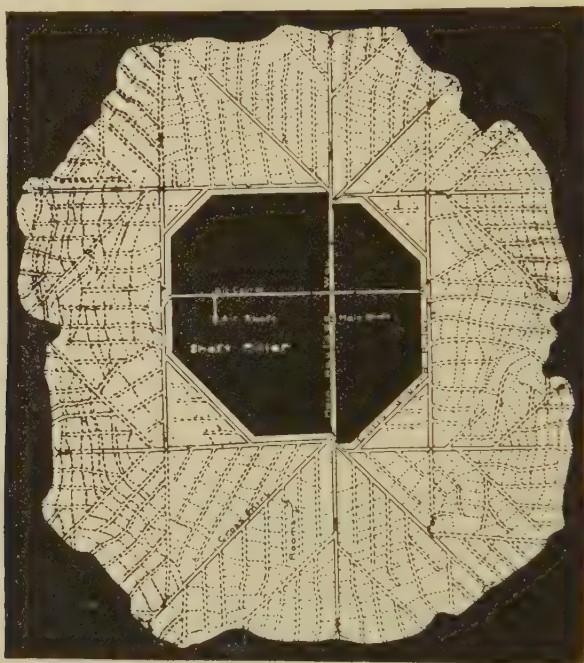


FIG. 143.—Plan of a longwall mine. Note the large block of coal left around the shaft to protect it. All the coal is removed as the mining proceeds outward. (After Bement, Ill. Geol. Survey Bull. 56, Fig. 18, p. 48.)

Wastefulness in Mining and Utilization of Coal.—The problem of fuel economy is of great interest. In spite of the fact that we live in a so-called “machine age,” our methods of mining and preparing our fuels for market and the machines used for converting them into useful mechanical power are extremely wasteful and inefficient. Dr. George O. Smith, director of the U. S. Geological Survey, pointed out this fact in 1920 in a very illuminating table which appears on p. 367.

That only 76 pounds, or 4 per cent, of the ton of coal mined actually becomes useful energy at the other end of the mechanical chain is somewhat appalling, making our so-called “efficiency” seem a chimera.

TABLE 66.—AMOUNTS LOST AND SAVED AND THE DIVISION OF THE LOSSES IN EACH TON OF STEAM COAL MINED IN THE UNITED STATES¹

	Number of pounds
Lost in mining.....	600
Consumed in mining coal.....	31
Consumed in transporting coal.....	82
Lost en route to boiler room.....	13
Lost in gases going up in stack (loss in firing).....	446
Lost by radiation.....	51
Lost in ash pit.....	51
Unavailable and lost in converting heat energy into mechanical energy.....	650
Converted into mechanical energy.....	76
	2,000

¹ SMITH, GEORGE O., *Power*, Nov. 2, 1920.

This same ton of coal could be made to produce far more power, as has been shown by the U. S. Geological Survey's investigations of the efficiency of super-power stations. If the small domestic power plants (relatively so inefficient) were replaced by superpower stations at favorable localities for power distribution, a much larger saving would result.

Mining of Anthracite.—Anthracite is mined largely by hand from mines whose arrangement is similar to that of bituminous mines. It is always sent through the breakers, where it is cleaned, sized, and often washed before being put upon the market. At present, washeries are working over the culm piles (waste materials from the breakers) that have been accumulating for years, and dredges are working over the gravels and sands of streams into which the fine material from the breakers was discharged. Millions of tons of anthracite that were supposed to have been lost are thus recovered. During the last century, the losses in anthracite mining were estimated to be as much as 70 per cent, but in 1893 the Anthracite Coal Waste Commission found them to be about 60 per cent. Through improvement of mining methods and by saving much coal once sent to the culm pile, the recovery is now still greater. The U. S. Geological Survey estimates that about one ton of anthracite is lost for each ton mined.

Methods of Mining Peat and Preparing It for Fuel.—Peat for fuel is cut from bogs by a turf spade or slade, a tool with a blade 10 inches long and 4 inches wide. Blocks about 4 inches square and 10 inches long are cut. They are piled up to dry for 4 weeks and are then stored.

Machine-pressed peat is much better for fuel, because, after having been thoroughly macerated, the raw peat is pressed into hard, firm blocks which can be readily handled. The best means of using peat for heating purposes is to convert it into producer gas. A ton of water-free peat may yield as much as 48,000 cubic feet of gas (152 B. t. u.), and the by-products increase the value still further. Peat in the form of a fine powder makes an excellent fuel. It can also be converted into coke and charcoal.

RESERVES OF COAL IN THE UNITED STATES

The United States has enormous bituminous and lignite reserves, constituting about 52 per cent of the world's estimated supply. Of the

TABLE 67.—UNITED STATES COAL RESERVES BY FIELDS AND STATES¹

Field and state	Area of coal, square miles	Bituminous coal, tons	Anthracite and semianthracite coal, tons	Lignite and sub- bituminous coal, tons
Appalachian field				
Pennsylvania:				
Anthracite area.....	480		19,056,300,000	
Bituminous area.....	14,200	102,154,000,000		
Ohio.....	12,660	85,270,000,000		
Maryland.....	455	7,300,000,000		
West Virginia.....	17,000	138,425,500,000		
Kentucky.....	10,270	61,513,000,000		
Virginia.....	1,900	19,600,400,000	817,000,000	
North Carolina.....	60	181,500,000		
Tennessee.....	4,400	23,289,500,000		
Georgia.....	167	846,600,000		
Alabama.....	8,373	61,327,600,000		
Total.....	69,965	449,908,100,000	19,873,300,000	
Interior field:				
Michigan.....	11,000	10,889,300,000		
Indiana.....	6,500	48,140,700,000		
Kentucky.....	4,900	50,400,000,000		
Illinois.....	35,600	182,758,400,000		
Iowa.....	12,560	26,461,000,000		
Missouri.....	23,960	76,225,000,000		
Kansas.....	18,600	27,223,200,000		
Oklahoma.....	10,000	49,865,200,000		
Arkansas.....	1,580	1,267,700,000	363,000,000	
Texas.....	8,200	7,259,500,000		
Total.....	132,900	480,490,000,000	363,000,000	
Gulf Coast field:				
Arkansas.....	100			81,700,000
Texas.....	2,000			20,871,000,000
Total.....	2,100			20,952,700,000
Rocky Mountain field:				
North Dakota.....	29,630			633,329,800,000
South Dakota.....	2,160			925,900,000
Montana.....	38,425	2,410,300,000		342,409,700,000
Wyoming.....	20,660	73,005,700,000		535,535,500,000
Colorado.....	14,341	193,442,500,000	456,400,000	104,533,600,000
New Mexico.....	13,120	17,173,700,000	7,200,000	156,903,000,000
Idaho.....	230	554,500,000		90,700,000
Utah.....	3,646	80,021,800,000		141,700,000
Arizona.....	3,610	9,100,000		12,832,500,000
Total.....	126,022	366,708,300,000	463,600,000	1,777,722,400,000
Pacific Coast field:				
Washington.....	1,800	10,355,700,000	21,100,000	47,588,800,000
Oregon.....	90			907,400,000
California.....	10	25,000,000		14,900,000
Total.....	1,900	10,380,700,000	21,100,000	48,511,100,000
Grand totals.....	339,887	1,357,487,100,000	20,721,000,000	1,847,186,200,000

¹ Data from CAMPBELL, M. R., *Report on Coal*, Twelfth International Geological Congress, vol. II, pp. 534-539, 1913.

coal reserves of the United States, less than 0.52 per cent is anthracite, 48.53 per cent is subbituminous and lignite, and 50.95 per cent is bituminous. A total of 496,766 square miles in the United States is underlain by coal, of which 250,531 square miles is anthracite and bituminous.

The estimate of the original coal content of the anthracite fields of the United States was 19,056,300,000 tons. The total production of anthracite from 1807 to 1926 was 3,562,896,361 tons. Assuming that for every ton produced since 1807, 1 ton has been lost, a total of 7,125,796,722 tons has been removed, which would leave 11,930,507,278 tons yet available. If the future annual production of anthracite remains about 90,000,000 tons (what it is at present) and the percentage recovery remains essentially the same (though a future higher recovery is probable), the reserves will last about 60 to 70 years longer.

Various estimates of the total reserves of coal in the United States have been made. M. R. Campbell prepared the figures of this country's coal reserves for the Twelfth International Geological Congress, of 1913, in which the reserves of the entire world were studied. Data for Table 67 are taken from his report. A later table by Campbell¹ gives a revision of these figures by which the amounts are somewhat increased, but material from the earlier table is used here because the total reserves for each state are given in it. Deducting the amount of coal used since Campbell made his estimate in 1913, there still remains in the United States (January, 1929) 3,527,000,000,000 tons of coal within 3,000 feet of the surface.

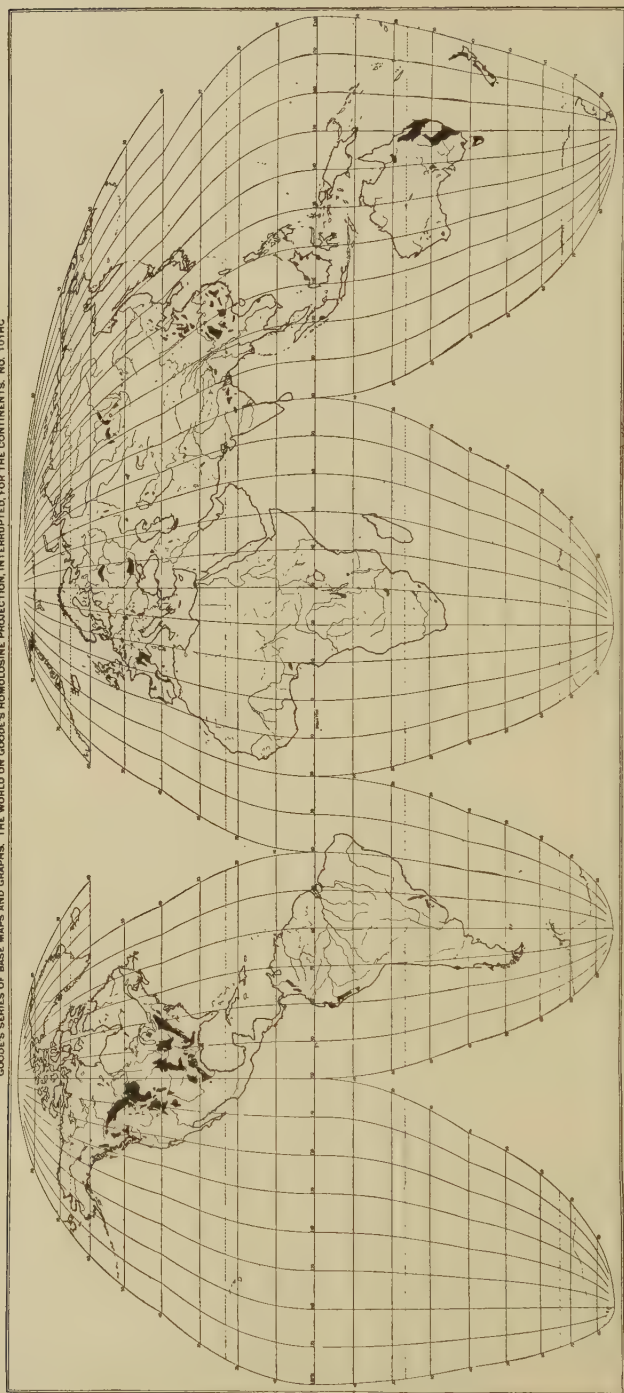
COAL DEPOSITS OF THE WORLD

Coal is utilized, in some degree, in practically all parts of the world. No less than 50 countries produced it in 1927 (Fig. 144), but only 3 of them exported large quantities (see Fig. 150, p. 377). Eight or ten other countries exported in limited amounts, and the remainder imported, either entirely, or in amounts sufficient to meet the requirements in excess of their own production if they were producers. Coal is sometimes imported from and exported to the same country; for example, the United States exports coal to Canada and Canada exports coal to the United States. This takes place when a market in one country is more readily supplied from a mine in the other country than it is from one in its own, which is quite likely to happen in the case of two adjoining countries the size of the United States and Canada.

The coal reserves of the world were made a special subject of study by the Twelfth International Geological Congress held in Canada in 1913. The results of the study were published in a three-volume report: "The Coal Resources of the World, 1913." The distribution of these reserves by kinds of coal is shown in Table 68.

¹ CAMPBELL, M. R., U. S. Geol. Survey *Prof. Paper* 100, pp. 1-33, February, 1917.

GOODE'S SERIES OF BASE MAPS AND GRAPHS, THE WORLD ON GOODE'S HOMOLOGICAL PROJECTION, INTERRUPTED, FOR THE CONTINENTS, NO. 1011C



For details see *Geographic History of the World*, by H. H. Goode, published by the University of Chicago Press, Chicago, Copyright 1913 by the University of Chicago

FIG. 144.—Coal deposits of the world. Black areas represent coal fields. (Data from all available sources.)

TABLE 68.—ESTIMATE OF THE COAL RESERVES OF THE WORLD¹

Kinds of coal	Amount, metric tons
Anthracite.....	496,846,000,000
Bituminous.....	3,902,944,000,000
Subbituminous, brown coals, and lignite.....	2,997,763,000,000
Total.....	7,397,553,000,000

¹ "The Coal Resources of the World, 1913," vol. I, p. 28.

Distribution and Age of Coal in the World.—The distribution of coal by continents is shown graphically in Fig. 145.

North America.—North America has the greatest reserves of coal of any of the continents. It contains about two-thirds of the world's supply. The Carboniferous coals include the high-grade coals, anthracite and bituminous, and are found in the eastern part of the continent. The Mesozoic and Tertiary coals of lower grade are in the western part; they extend from southern United States, through Canada, to Alaska. The United States has larger reserves of bituminous coal than any other country in the world.

Asia.—Asia contains the next largest coal reserve. Her estimated amount may be increased as geological exploration extends into relatively unknown parts of China and Siberia. Asia's most important coal reserves are Carboniferous in age (Tertiary next). Mesozoic coals occur but are not very important. China's anthracite deposits (Carboniferous) in the province of Shansi are the largest in the world (estimated to contain 80 per cent of the world's anthracite). China and India are the chief coal producing countries of Asia.

Europe.—Europe has only about 10 per cent of the world's coal reserves and about 17 per cent of the high-grade coals, yet her production in 1926 was approximately 44 per cent of the world's coal production that year. Carboniferous coals occur from Great Britain to Russia. Mesozoic and Tertiary coals are distributed locally. In 1926, Germany for the first time led in coal production in Europe, having surpassed Great Britain. Great Britain was second, and next in order were France, Poland, Russia, and Belgium.

Australia.—Australia and the nearby islands have a considerable reserve of coal, much of it of excellent grade. The major part of it comes from the southern part of the continent. Tasmania and New Zealand

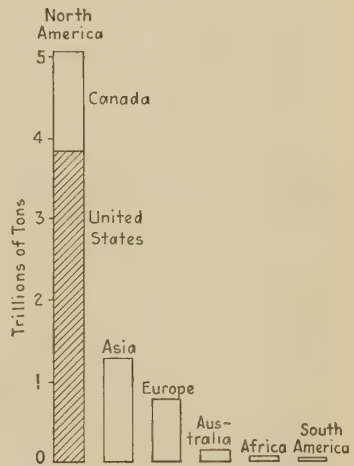


FIG. 145.—Coal resources of the world by continents.

contribute to the production, and a limited amount comes from the East Indies.

Africa.—Africa has limited coal reserves. Most of the production comes from South Africa, where the coal is anthracite and bituminous of Carboniferous age. Small amounts come from Rhodesia and Nigeria, also.

South America.—South America has very small coal reserves. They are located in Colombia, Chile, and Peru. Both Paleozoic and Tertiary coals occur. Chile produces about 1,500,000 tons of coal annually, and the other countries only very small amounts.

USES OF COAL

It may seem unnecessary to do more than mention the uses of coal, yet there are several interesting points in connection with them. Coal is, at the present time (1929), absolutely essential as a fuel and as a source of power, although its supremacy in both fields has been threatened in recent years. People living in the temperate zone with its low winter temperatures must have a source of warmth. Formerly, wood sufficed, but modern man demands a more concentrated fuel, and this demand is met by some variety of coal.

Anthracite.—Anthracite is preferred as a fuel for domestic purposes because of its cleanness, but unfortunately all of the anthracite mines of the United States are located in the extreme eastern part, so that even the greater heating power and cleanness of anthracite cannot offset its greater cost at the more distant points. In 1927, 71.2 per cent of the anthracite mined was used for domestic purposes, and 28.8 per cent was used as a steaming coal. Various names are applied to the different sizes of anthracite as follows: *broken*, *egg*, *stove*, *chestnut*, *pea* (all primarily for domestic use), *buckwheat* (Nos. 1, 2, and 3), and *boiler*.

Bituminous Coal.—Bituminous coal has a wide geographic distribution and a resulting shorter haul to the user. The lower grades are, of course, restricted to local use. Our industries use a tremendous amount of coal as a source of power, although in them, as well as in the case of domestic heating, other sources of power are encroaching upon the use of coal. The U. S. Geological Survey, a few years ago, analyzed the uses to which our coal production was put and arrived at the following estimate for bituminous coal: 80 per cent used for power by railroads, industrial plants, public utilities, and in coke making; 16 per cent used by domestic consumers; and the remainder (4 per cent) exported.

Much bituminous coal is used in the manufacture of coke (which will be discussed separately) and in gas making. Recently, it has been distilled to produce gasoline and other hydrocarbons. As yet, this process is carried on only where the price of gasoline is high enough to invite competition. Undoubtedly, such a production will become important

in the future, unless some new fuel for internal-combustion motors is discovered.

Peat.—Very little of the peat dug in this country is used for fuel, in spite of the fact that a ton of machine-pressed peat has a heating value equal to 1.3 tons of wood, 0.7 ton of bituminous coal, or 0.5 ton of anthracite.

The most important use of peat in the United States is as a fertilizer or in making fertilizers. The value of peat as a fertilizer is due to its high content of combined nitrogen (in some dried peats as high as 2 per cent), which is recovered as ammonium sulfate (a costly ingredient that must be added to fertilizers). Some peats contain a little nitrate and potash, also. Peat mull is an excellent absorbent of the valuable nitrogenous liquid of stables, whereupon it becomes a very valuable fertilizer. One hundred pounds of peat will absorb from two to three times its own weight of water.

Another common use of peat is as a stock food or, rather, as a stimulant; for, mixed with foods, it causes an increase of appetite. It is also used as bedding for stock.

Pure peat is an excellent disinfectant and thus may be used as an antiseptic dressing for wounds instead of medicated cotton. Other minor uses are for packing, manufacture of paper and woven fabrics, as artificial wood, and in making mattresses and sanitary appliances.

The Threatened Supremacy of Coal.—The U. S. Bureau of Mines¹ has recently pointed out the competition taking place against coal as a source of power. "The consumption of all kinds of coal increased only 3.3 per cent from 1913 to 1925, but the consumption of natural gas for power increased 104 per cent, of petroleum 211 per cent, and of water power 119 per cent." The percentage of heating value contributed

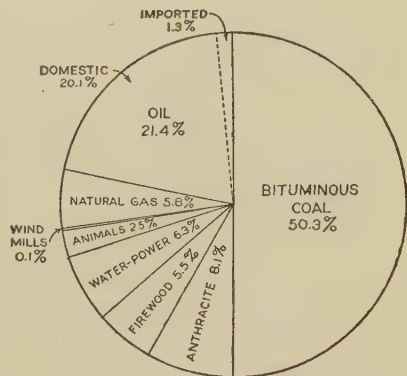


FIG. 146.—Sources of the energy supply of the United States in 1927, including that derived from work animals, windmills, and firewood. (*U. S. Mineral Resources, 1927, Part. 2, p. 405.*)

by each type of fuel is shown by the following chart (Fig. 146). The water power used (1927) was equivalent to 7.3 per cent of the fuels. The total horsepower developed by water-power plants in the United States is only about 15 per cent of the total potential water power. During the 5 years from 1920 to 1925, the petroleum used as a source of power was equal annually to 70,000,000 tons of coal. A large quantity of petroleum is used for domestic heating, also. It was estimated in 1927 that over 700,000 homes in the United States had oil fuel systems.

¹ *U. S. Mineral Resources, 1925, Part 2, p. 394.*

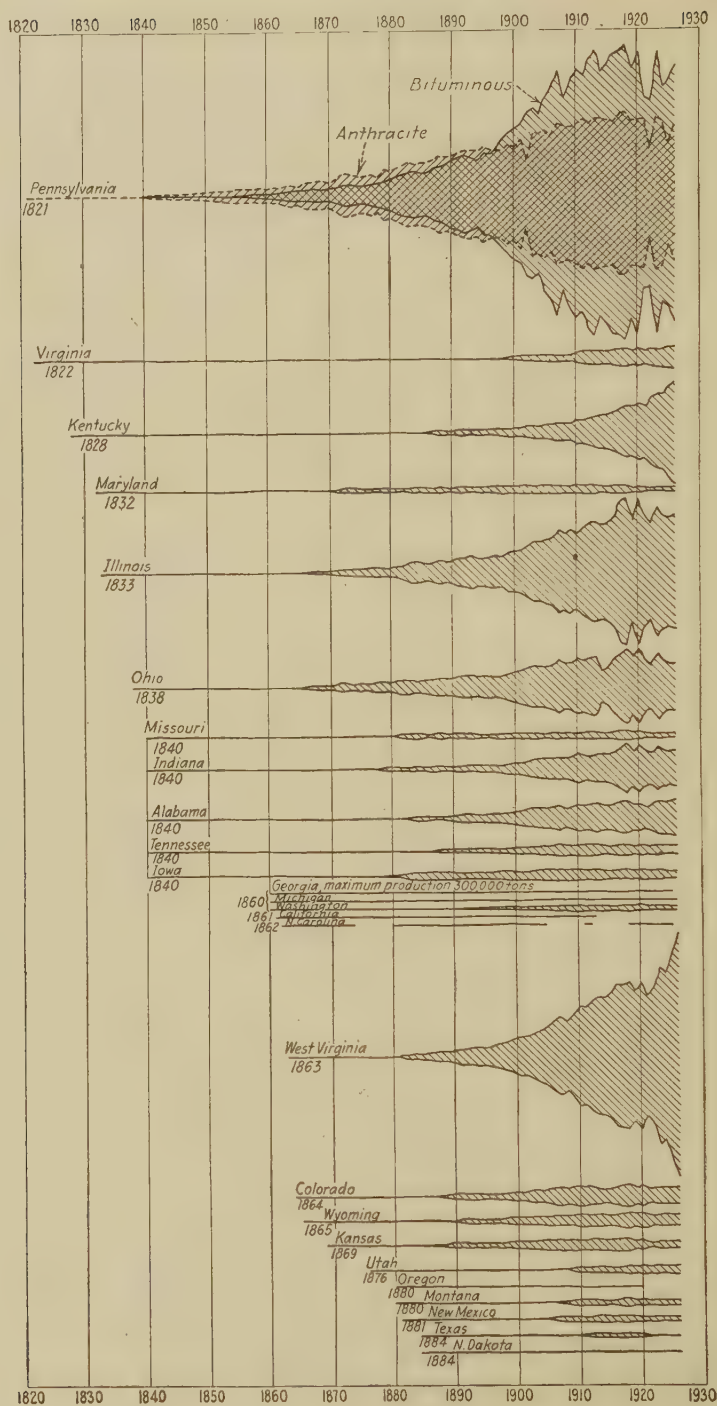


FIG. 147.—Date of initial production and annual production of coal in each state. Vertical scale, 1 mm. = 4,500,000 tons. (Data from U. S. Geol. Survey.)

PRODUCTION OF COAL IN THE UNITED STATES

Production of coal in the United States began over 100 years ago. The date of initial production and the amount of coal mined annually in each state is shown graphically in Fig. 147. The figure also shows that the major part of the total production for the entire United States has come from a few states. Although anthracite was produced first, most of the production has been bituminous coal. An examination of the curves (Fig. 124, p. 340) giving the production of bituminous and anthracite coal since 1820 shows the following facts: (1) a very slow growth in production during a period of 50 years (1820 to 1870), (2) an extraordinarily rapid increase for the next 50 years (1870 to 1920), and (3) apparently the entrance to another period of nearly stationary production or a very slow rate of increase (1920).

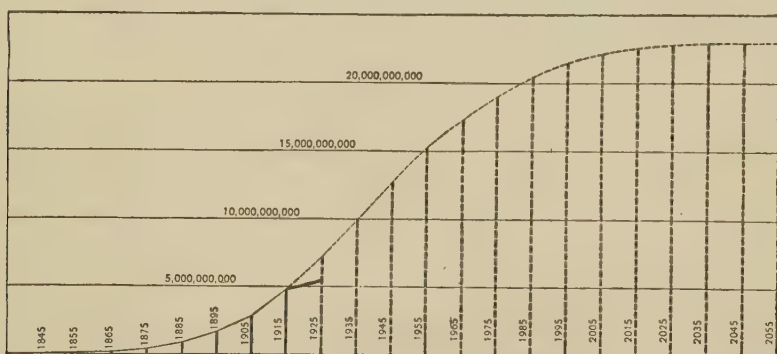


FIG. 148.—Estimated production of coal in the United States to the year 2055. The heavy black line between 1915 and 1925 has been added by the author to show the actual trend of production for that decade. (After E. W. Parker.)

The peak of production (678,212,000 long tons) came during the last year of the World War, although the output of 1920, 1923, and 1926 nearly reached the high mark of 1918. Fluctuations are frequent, but apparently the maximum has been reached. The utilization of other fuels and of water power has been a contributing factor in bringing the rate of coal production nearly to a standstill.

Estimates of Future Production.—Many attempts are made to predict the probable future production of coal. Usually the rate of increase over a period of years is the basis for such estimates. The rate of increase before the war was about 18,000,000 long tons annually, but this was increased to 22,700,000 during the war. Had this rate of increase been maintained, the production in 1926 would have been 860,170,000 long tons. Actually, it was 657,804,000 long tons. E. W. Parker¹ in 1908 estimated the future coal production in the United States for the decade

¹ PARKER, E. W., *Mines and Minerals*, pp. 462–465, 1908,

ending 1925 as about 7,200,000,000 tons. The actual production for this period was 5,932,000,000 tons, which is about 82 per cent of the estimated amount. Campbell¹ has represented Parker's results graphically (Fig. 148).

Gannett,² by means of a hyperbolic curve based on a formula deduced from previous productions, estimated in 1909 that 21,000,000,000 tons of coal would be produced in the United States from 1908 to 1927. The actual production was only slightly more than 50 per cent of the estimate. Not much value can be placed upon estimates of future production.

ARTIFICIAL COKE

Coke is a gray, hard, brittle, porous material. It consists dominantly of fixed carbon and ash (see following table of analyses of original coals and the resulting coke).

TABLE 69.—ANALYSES OF ARTIFICIAL AND NATURAL COKES AND THE ORIGINAL COALS

Constituents	Coal ¹ (from Pratt bed, Alabama)	Coke ¹ (made from coal of Pratt bed)	Coal ² (from Con- nellsville, Pa.)	Coke ² (made from Con- nellsville coal)	Coal ² (from Primero bed, Ra- ton field, Colorado)	Natural coke ² (formed by dike cutting Primero bed)
Moisture.....	2.88	.....	2.82	0.79	2.28	
Volatile matter.....	29.56	1.03	29.97	1.31	29.81	8.31
Fixed carbon.....	56.91	87.58	59.84	86.88	58.75	80.92
Ash.....	10.65	10.88	7.37	11.54	9.16	10.77
Sulfur.....	2.04	1.19	1.22	0.70	0.50	0.63

¹ U. S. Geol. Survey *Bull.* 400, pp. 177-185.

² U. S. Bur. Mines *Bull.* 22, Part 1, pp. 70, 168.

Most coke is manufactured from bituminous coal, but a considerable amount is produced during the refining of petroleum and the manufacture of coal gas and coal tar. This petroleum coke is not strong enough for use in blast furnaces and foundries, hence it is used for domestic and other purposes. Coke resulting from the manufacture of coal gas (especially gas-house coke) finds a ready market for making water gas and for domestic uses. The amount of coke produced in the five countries leading in the production of coal (and coke) is shown in Fig. 149.

¹ CAMPBELL, M. R., *The Coal Fields of the United States*, U. S. Geol. Survey *Prof. Paper* 100, p. 26, 1917.

² GANNETT, HENRY, *Estimate of Future Coal Production*, U. S. Geol. Survey *Bull.* 394, pp. 27-29, 1909.

THE MANUFACTURE OF COKE

Since coke must contain a high percentage of fixed carbon, the coal is heated in closed ovens out of contact with the air. The volatile constituents are thus driven off and the carbon content is increased. The process is carried on in two types of ovens: the *beehive oven* and the *retort oven* (commonly called the *by-product oven*). The beehive oven was the first type used in the United States; but, because all the gases and other products liberated during the coking process are lost in such an oven, it is now being replaced by the by-product (or retort) oven, which saves all the by-products formed. The by-product method also makes possible

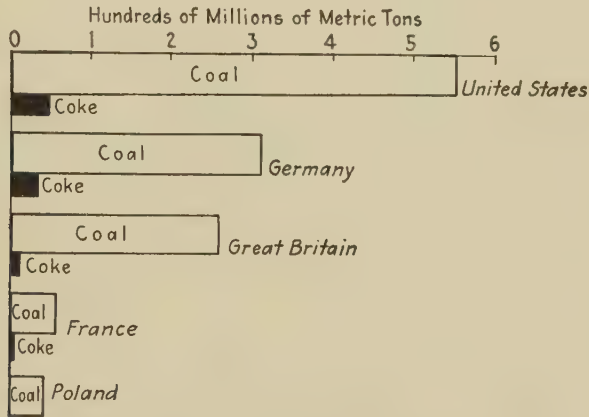


FIG. 149.—Amount of coal and coke produced in each of the five leading countries in 1927.
(Data from *U. S. Mineral Resources, 1927, Part 2, p. 457.*)

a larger production of coke from each ton of the original coal. Where the beehive oven yields 65.2 per cent, the by-product oven yields 69.9 per cent of coke to a ton of coal. In spite of the greater wastefulness of the beehive method, however, its withdrawal from use in the United States is slow. The number of beehive ovens in 1910 was 100,000 and since then has declined to only one-half that number. The first production made in this country from by-product ovens was in 1893, but so slowly were they adopted that their production did not surpass that of the beehive ovens until 1919 (see Fig. 150). Other countries have long since abandoned the wasteful beehive method, but it is *still* extensively used in the United States. In 1927, there were 49,795 beehive ovens and 12,475 by-product ovens, and yet the latter produced 85.9 per cent of our coke production that year.

The Beehive Method.—The beehive oven has the shape suggested by its name. It is usually about 12 feet in diameter and 6 to 7 feet high.

The coal is placed in the oven (which is hot), and the heat from the walls drives off and ignites the volatile matter. The oven is then closed up, save for an opening in the top through which the distilled gases escape. The volatile hydrocarbons, moisture, and sulfur are largely driven off (and lost) and the carbon remains behind as a brittle, porous mass. The time required for this process varies from 48 to 72 hours. A mechanical ram pushes the finished coke products out of the oven, and a new charge is immediately put in.

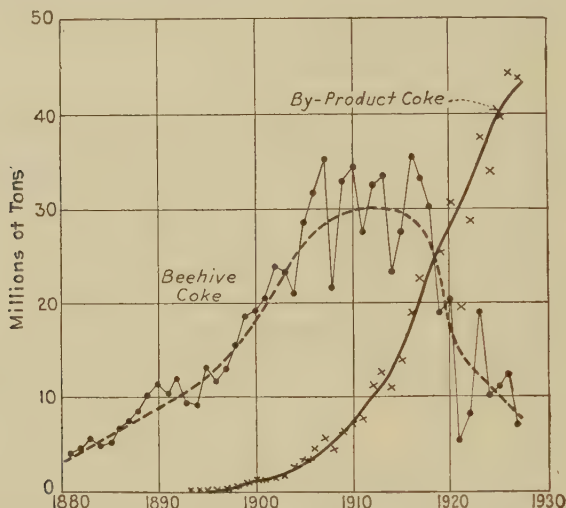


FIG. 150.—Curves showing the increase in the production of by-product coke and the decline in the production of beehive coke. (Data from U. S. Mineral Resources, 1927, Part 2, p. 605.)

The By-product Method.—The by-product oven is really a retort, into which the coal is charged and the heat applied externally. These retorts are about 33 feet in length, 7 feet in height, and from 15 to 20 inches in width. They are arranged in units of from 25 to 35 and are heated by gas. The narrow chamber speeds up the process of coking, requiring only about one-half the time necessary in the beehive oven and also producing a better grade of coke. The gas and other volatile matters driven off from the coal are sent through various cleaning and sorting appliances and condensers. The value of these by-products is alone sufficient reason for the more extensive use of the by-product oven.

Value of the By-products.—The value of the by-products of coke making in the United States in 1927 was \$3.66 to every ton of coke produced. The total production and value of these by-products in the United States for one year is shown in the following table:

TABLE 70.—AMOUNT AND VALUE OF BY-PRODUCTS AND BY-PRODUCT COKE IN THE UNITED STATES, 1926¹

By-products	Production	Value of products sold
Tar.....	529,486,004 gal.	\$ 14,103,000
Ammonia:		
Ammonium sulphate.....	1,167,859,000 lb.	24,658,000
Ammonia liquor (NH ₃ content).....	53,523,000 lb.	3,470,000
		\$ 28,128,000
Gas.....	706,681,000,000 cu. ft.	64,686,000
Light oil and derivatives:		
Crude light oil.....	164,059,000 gal.	1,330,000
Benzol, crude.....	4,774,000 gal.	1,109,000
Benzol, refined.....	17,713,000 gal.	3,957,000
Motor benzol.....	90,029,000 gal.	16,863,000
Toluol, crude.....	432,000 gal.	127,000
Toluol, refined.....	8,359,000 gal.	2,787,000
Solvent naphtha.....	4,704,000 gal.	1,035,000
Other light oil products.....	4,127,000 gal.	93,000
		\$ 27,304,000
Napthalene:		
Crude.....	7,746,000 lb.	96,000
Refined.....	139,000 lb.	1,000
		\$ 97,000
Total value of all by-products sold.....		\$134,469,000
By-product coke.....	44,376,586 ton	250,748,533

¹ U. S. Mineral Resources, 1926, Part 2, p. 648.

The following table shows the amount of coke and of each by-product obtained from 1 ton of coal:

TABLE 71.—AVERAGE YIELD OF COKE AND BY-PRODUCTS PER NET TON OF COAL IN THE UNITED STATES, 1927¹

Product and by-products	Yield per ton of coal
Coke.....	1,388.0 lb.
Tar.....	8.6 gal.
Ammonium sulphate (or equivalent).....	22.7 lb.
Light oil.....	2.9 gal.
Gas.....	11,100.0 cu. ft.

¹ U. S. Mineral Resources, 1927, Part 2, p. 652.

Good Coking Coals.—Not all bituminous coals are satisfactory coking coals. Many are too high in ash, others too high in sulfur, and still others do not have the proper amounts of volatile matter and fixed carbon. Pishel¹ has shown that a simple test of coking quali-

¹ PISHEL, MAX A., A Practical Test for Coking Coals, *Econ. Geol.*, vol. III, pp. 265-275, 1908.

ties can be made by grinding a coal in a mortar. If it adheres to the sides of the mortar, it is a good coking coal. A coal having a high volatile-matter content is slow in coking, and one that is low in volatile matter cokes quickly. The Pocahontas coal is a fine example of the latter kind and is largely used for coking in Pennsylvania, West Virginia, and other eastern states. Though the Pittsburgh coal is high in volatile matter, it cokes relatively quickly. The coals of eastern Kentucky and West Virginia, as well as those of Illinois and Indiana, are high-volatile coals and coke slowly. These two types of coal are often mixed before coking.

USES OF COKE AND BY-PRODUCTS

Use of Coke.—Coke is an indispensable fuel in blast furnaces, as shown by the parallelism of the production curves for coke and pig iron in Fig. 151. For the production of each ton of pig iron in the United



FIG. 151.—Diagram showing the parallelism of coke and pig iron production in the United States. (Data from U. S. Bur. Mines.)

States in 1927, slightly more than 1 ton, *i.e.*, 2,094 pounds, of coke was used. Copper, lead, and zinc smelting require considerable coke, also. The various furnaces use nearly 80 per cent of the annual coke production, and foundries use an additional 3,000,000 tons. The remainder is employed for domestic and various industrial purposes.

Uses of the By-products.—The by-products of coke making have numerous and extremely varied uses. An enormous number of organic compounds are derived from them, and further products are obtained by synthetic processes. The stimulus to save these products in the United States came during the World War. Although the war-time uses no longer exist, other markets have arisen, so there is still a ready sale for them.

Tar.—Tar is sold to refiners, who extract from it a long series of organic compounds which form the basis of the coal-tar industry. The tar coke left from this refining is sold for fuel. The other important use of tar is as a fuel. Because of its high heating power (about 16,000 B. t. u. per pound), which is greater than that of coal but less than that of fuel oil, it has a ready market. (The heating power of fuel oil ranges from 17,000 to 20,000 B. t. u.) Tar is used especially by the open-hearth steel plants, because by its use the cost of producing a ton of steel is lowered about 10 per cent. Over 250,000,000 gallons of tar was used by furnace plants in 1926.

Ammonia.—Ammonia, NH_3 , and ammonium sulfate are used mainly in the fertilizer industry; the remainder of their production goes into explosives, chemicals, and refrigerating processes.

Benzol and Toluol.—Benzol and toluol (also called “benzene” and “toluene”) are two very important products which come from the light oils, and there are also a number of minor light oils. During the World War, these two products were used in making explosives; toluol in making T. N. T. (trinitronol), and benzol in making picric acid. They commanded enormous prices at that time. At present (1928), they are used as motor fuels. Toluol and benzol are present in the light oils in the ratio of 1: 5, respectively. Both may go into the gasoline, which is then put on the market as benzol gas. Other uses of benzol and toluol

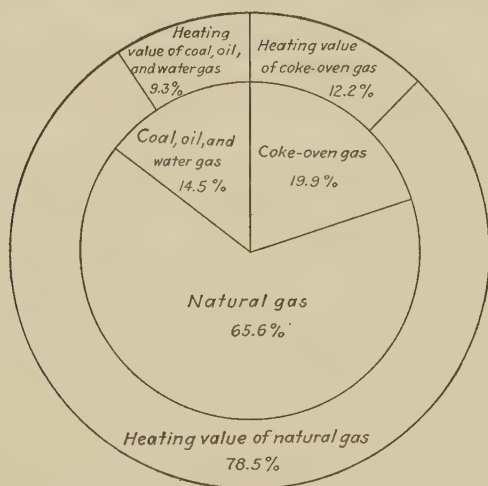


FIG. 152.—Diagram showing the production (inner circle) and heating value of the three dominant gas fuels. (Data from *U. S. Mineral Resources*, 1926, Part 2, p. 669.)

are in the manufacture of dyes, organic chemicals, and as solvents for paints and varnishes.

It is of much interest to note that the low-temperature carbonization of coals is being rapidly developed in those countries where much or most of the gasoline or kerosene is imported. Distilling the coal at low temperatures greatly increases the yield of the higher grades of light oils, which include gasoline and benzene. Germany is making rapid progress in this field. Various names are given to these synthesized products, and undoubtedly their production and use will become widespread in certain countries. At present, the benzol production in this country is only a fraction of the gasoline production.

Gas.—Of the gas produced by the by-product ovens in the United States, 41.6 per cent is used in the coking process, 56.6 per cent is sold for heating and lighting purposes, and 1.8 per cent is wasted. The

heating power of coke-oven gas before the benzol is removed is from 530 to 630 B. t. u. per cubic foot; its average value after the removal of the benzol is 550 B. t. u. The heating value of natural gas is about 1,000 to 1,200 B. t. u. The heating power of ordinary coal gas is from 550 to 600 B. t. u. The percentages of total production and heating value of gas fuels are shown graphically in Fig. 152.

Napthalene.—Napthalene is employed extensively in the manufacture of coal-tar dyes. About one-third of the production of refined napthalene is said to be used in the form of flakes and balls for protection against moths.

Selected Readings on Coal

The following references are general and contain a wide range of information as to the character, composition, mode of occurrence, distribution, origin, and uses of coal. ASHLEY, G. H.: The Maximum Rate of Deposition of Coal, *Econ. Geol.*, vol. II, p. 34, 1907.

BRIAN, E. J.: Contact Metamorphism of Some Colorado Coals, *Am. Inst. Min. and Met. Eng.*, vol. LXXI, pp. 246–252, 1925.

CAMPBELL, M. R.: Hypothesis to Account for the Transformation of Vegetable Matter into the Different Varieties of Coal, *Econ. Geol.*, vol. I, pp. 26–33, 1905.

CLARKE, F. W.: Coal, Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, pp. 756–782. Excellent summary of the origin of coal.

DAVIS, C. A.: Peat Deposits of the United States, U. S. Geol. Survey *Bull.* 394.

— and BASTIN: Peat Deposits of Maine, U. S. Geol. Survey *Bull.* 376.

EMMONS, W. H.: "General Economic Geology," pp. 10–102, McGraw-Hill Book Company, Inc., New York, 1922.

JEFFERY, E. C.: The Mode of Origin of Coal, *Jour. Geol.*, vol. XXIII, p. 218, 1915.

MOORE, E. S.: "Coal, Occurrence and Properties," John Wiley & Sons, Inc., New York, 1922

RIES, H.: "Economic Geology," pp. 1–69, John Wiley & Sons, Inc., 1925. Contains a long list of references on coal.

STEVENSON, J. J.: The Formation of Coal Beds, *Am. Phil. Soc., Proc.*, vol. L, 1911; vol. LI, 1912; vol. LII, 1913. This is a very good discussion of the formation of coal.

"The Coal Resources of the World," 3 vols. and atlas, Morang and Co. Ltd., Toronto, 1913. This gives a complete summary of the known information regarding the coal deposits of the world. It was issued in connection with the Twelfth International Geological Congress.

WHITE, DAVID: The Origin of Coal, U. S. Bureau Mines *Bull.* 38. Also contains a chapter on The Formation of Peat by C. A. Davis. Later papers on coal by White are: (1) Treatise on Sedimentation, pp. 266–289; (2) Environmental Conditions of Deposition of Coal, *Am. Inst. Min. and Met. Eng.*, vol. 71, pp. 3–34, 1925; (3) Progressive Regional Carbonization of Coals, *idem*, pp. 253–281. There are several other valuable papers by R. Thiessen, E. C. Jeffery, and C. A. Seyler in this same volume.

The numerous bulletins and other papers of the U. S. Geological Survey have a wealth of information about coal. Individual state reports cover their respective coal deposits.

U. S. Mineral Resources has an abundance of data regarding production and the innumerable factors that influence it. The 1910 volume is very good.

CHAPTER XIII

PETROLEUM AND NATURAL GAS

Petroleum and natural gas are fundamentally important in the civilization of today. The value of the petroleum and its distillation products (gasoline, kerosene, benzene, naptha, lubricating oils, paraffin, and asphalt) used in the world today (1928) greatly exceeds that of any other earth material used by man. Everyone knows the part which these products play in our daily life. Each has its own use, and all of them are so familiar that we regard them as indispensable, which they actually are. One of the most vital problems of the present period is the conservation of our declining reserves of petroleum, since petroleum once used is lost forever. There is no evidence that it is being formed at the present time in amounts sufficient to replace those removed. Producers of petroleum are making every effort to obtain the maximum production from the ground, and the refiner is constantly seeking new processes for extracting larger quantities of gasoline, kerosene, and other oils from the crude petroleum. An improvement in the mechanical efficiency of gasoline motors is much needed, as they are used so extensively. The total horsepower of internal-combustion engines of pleasure automobiles in the United States is more than double that used for all industrial purposes.

Petroleum contains many minor substances also which are of use to man, although at present these uses are but slightly known. The possibilities of many of these substances may be great, but little is being done to determine the extent of their uses.

Natural gas is another important fuel, of which we are using (and wasting) enormous amounts. It is an ideal fuel, giving the maximum amount of heat of any gas and being colorless and odorless.

PETROLEUM

The word *petroleum* comes from the Greek words *petra* meaning rock and *oleum*, oil. Petroleum thus means *rock oil*, a name which is sometimes still applied to it. It has various other names: *coal oil*, *earth oil*, *mineral oil*, *natural oil*, and *seneca oil*, but petroleum or just *oil* is the name which should be used.

History. *Petroleum in Ancient Times.*—Petroleum has been known from ancient times. It was first found floating on the water of springs. Very likely, the "perpetual fires" of the ancients were such springs burning. The people of Babylonia and Nineveh used it in building operations.

Herodotus tells of an oil spring on the island of Zante (formerly Zacy-nothos) along the west coast of Greece. The Romans secured petroleum from Sicily and burned it in lamps.

Early Accounts of Oil in the Americas.—The first account of petroleum's being found in either of the Americas was made in 1595 in Sir Walter Raleigh's publication about the pitch lake on the island of Trinidad. In describing the lake, he said:

At this point, called *Tierra de Brea* or *Piche*, there is that abundance of stone pitch that all the ships of the world may be therewith laden from thence; and we made trial of it in trimming our ships to be most excellent good, and melteth not with the sun as the pitch of *Norway*, and therefore for ships trading the south parts very profitable.

The first recorded instance concerning oil in North America was in 1627 in a letter written by a Franciscan missionary. He describes an oil spring at a place near the present town of Cuba in Allegany County, New York. In 1748, Peter Kalm, a Swedish naturalist, visited North America; and, later in a book about his travels, he located on a map the oil springs near Oil Creek, Pennsylvania. Other springs are mentioned by writers later in the century. One account, in a letter from Gen. Benjamin Lincoln, 1783, to Rev. Joseph Willard of Cambridge University, tells how soldiers, halting at a spring in Oil Creek, bathed their joints with oil (called "Barbadoes tar") and how it eased the pain in them. They also drank freely of the waters, which "operated as a gentle purge."

First Uses of Petroleum.—In the early part of the nineteenth century, petroleum was used mainly for medicinal purposes. In 1833, a small vial of it sold, according to S. P. Hildreth,¹ for 40 to 50 cents. It was used somewhat for illuminating purposes but was found unsatisfactory on account of its peculiar odor. This could be prevented, it was found, by first filtering the oil through charcoal. The oil was also utilized as a lubricant.

Oil Secured from Wells Drilled for Other Purposes.—The first petroleum secured by drilling in the United States was in 1806 from a well drilled for brine. The oil was purely incidental and for many years was considered a nuisance. This well, which was 58 feet deep, was located near the Great Salt Lick in West Virginia. Other wells followed; some produced 25 to 50 barrels of oil per day. A well (known as the "American") drilled in 1829 on Little Pennox Creek, Cumberland County, Kentucky, furnished many thousands of barrels of oil. This was bottled and sold as "The American Medicinal Oil, Burkesville, Ky." S. M. Kier, a druggist of Pittsburgh, Pennsylvania, noted that the "American Oil" prescribed for his wife was similar to the petroleum obtained from a brine well, 400 feet deep, on his father's farm at Tarentum, Pennsylvania. He soon put "Kier's Petroleum or Rock Oil" on the market. It was widely

¹ HILDRETH, S. P., *Am. Jour. Sci.*, vol. XXIV, p. 63, 1833.

advertised for its curative powers. The following verse appeared on the bottom of a circular issued about it in 1850:

The healthful balm, from Nature's secret spring,
The bloom of health, and life, to man, will bring;
As from her depths the magic liquid flows,
To calm our sufferings and assuage our woes.

Another circular bore the number "400," which called attention to the depth from which the oil was secured and, without any change, bottled for use.

Early Efforts at Distillation.—In 1849, after James Young, a Scotchman, had developed a method of distilling illuminating oil from coal and shale, many plants were built in America, and "coal oil" was produced. On Mar. 4, 1858, nine barrels of petroleum from Tarentum, Pennsylvania, were purchased (for \$275.19) by the Kerosene Oil Company of New York, from which Luther Atwood and Joshua Merrill of the company were able to distill an excellent illuminating oil. Kerosene lamps were invented and were distributed free of charge to purchasers of kerosene. The new industry developed rapidly and completely ruined the business of distilling kerosene from coal; but, as only limited amounts of petroleum were available for distillation, it did not attain its full development until drilling for oil had become successful.

Drilling for Oil.—A New York company engaged Col. E. L. Drake to drill a well in 1859. He struck oil at 69 feet, producing a 25-barrel well. This was the first well in the United States which was drilled for oil. It was located on Oil Creek, Venango County, Pennsylvania. The total yield in 1859 was less than 2,000 barrels.¹ A period of great excitement followed. Wells were drilled everywhere; some were 400 to 500 feet deep. The search for petroleum began in Ohio, West Virginia, and California in 1876, in New York in 1880, and in Kentucky and Tennessee in 1883. Real production began in Ohio with the discovery of the Lima field in 1885. Production in Colorado began in 1887; in Indiana, Illinois, Kansas, Texas, and Missouri in 1889; and followed in rapid succession in other states. The greatest development occurred after 1900. Today (1929), the oil industry is enormous, not only in the United States but also in all parts of the world.

Composition.—Petroleum is an extremely complex mixture of several compounds of *carbon* and *hydrogen* with some *oxygen* and *nitrogen*. An ultimate analysis of a Pennsylvania light oil (gravity 39.31° A. P. I.) showed the following composition:

Percentage
C = 82.0
H = 14.8
O + N = 3.2

¹ An excellent account of this early period, with numerous illustrations, is found in Bacon and Hamor's "The American Petroleum Industry," vol. I, Chap. V.

The compounds comprising petroleum have a wide range in composition, and, as a result, two samples of petroleum are never alike. These compounds include benzene, gasoline, kerosene, naphthalene, lubricating oil, paraffin, and asphalt. In the process of refining crude oil, the compounds are given off at different temperatures. Those with the lowest boiling points go off first. The final residue may be liquid or solid, and it has various uses depending on whether it is essentially paraffin or asphalt. Petroleum coke is a valuable end product from asphaltic or mixed asphaltic and paraffin oils. Tables showing the composition of petroleum usually give the percentage of the different fractions. It is of more general interest, however, to know the amounts of gasoline, kerosene, and other products; hence, these are given in the accompanying table:

TABLE 72.—PERCENTAGES OF DIFFERENT OILS OBTAINED BY DISTILLING CRUDE PETROLEUM FROM SEVERAL FIELDS IN THE UNITED STATES

Locality	Grav- ity, A. P. I.	Benzenes (includes gasoline and naph- thas)	Kero- sene	Gas oil	Wax dis- tillate, lubricat- ing oils, and paraffin	Sul- fur	Residue (fuel oil, asphalt, paraffin, etc.) or loss
California:							
Ventura field.....	29.50	31.00	7.20	19.80	15.00	1.00	25.00
Rosecrans field.....	36.40	38.80	6.60	.....	.....	0.57	.....
Pennsylvania (average of many oils)	.....	23.50	42.00	.....	31.00	....	4.00
Montana:							
Cat Creek field (aver- age).....	47.40	56.80	29.60	.....	10.00	1.00	1.60
Colorado:							
Rangely field.....	.....	28.00	42.00	.....	30.00	....	.....
Arkansas:							
Champagnolle field..	34.00	28.00	20.60	7.40	.....	....	43.00
Champagnolle (as- phaltic oil).....	27.30	24.50	.....	20.20	.....	....	54.30
Oklahoma:							
Seminole field.....	39.60	38.60	4.90	.....	.....	0.33	.....
Cushing field.....	.....	30.90	25.00	15.00	.....	....	27.00
Texas:							
Panhandle field.....	35.80	22.30	17.10	.....	.....	0.62	.....
Electra field.....	.....	25.70	25.87	9.33	.....	....	36.77

Physical Properties. *Specific Gravity.*—The general character of crude petroleum is indicated by its specific gravity. The heavier grades are higher in asphalt and substances removed only at high temperatures during refining; the lighter grades yield more benzene, naphtha, gasoline,

kerosene, and paraffin. All petroleum are lighter than water. The range of their specific gravity is from 0.690 to 0.996. The gravity for any one field is fairly uniform.

This natural scale is not used, however, in determining the gravity of oil, but one in which the specific gravity is stated in degrees A. P. I. or degrees Baumé. Through agreement, the A. P. I. scale has replaced the Baumé. Neither of these scales has any advantage over the natural one, and it is hard to understand why the oil industry should have discarded that used by all other industries. The following table gives designated specific gravities and their equivalents in degrees A. P. I. and Baumé:

 TABLE 73.—SPECIFIC GRAVITY¹

Specific gravity	Degrees A. P. I.	Degrees Baumé
1.000	10.00	10.00
0.975	13.65	13.60
0.950	17.45	17.40
0.925	21.47	21.35
0.900	25.72	25.55
0.875	30.21	30.00
0.850	34.97	34.70
0.825	40.02	39.70
0.800	45.38	45.00
0.775	51.08	50.65
0.750	57.17	56.60
0.725	63.67	63.10
0.700	70.64	70.00
0.675	78.13	77.40
0.650	86.19	85.40
0.625	94.90	94.00
0.600	104.33	

¹ Bur. Standards Circ. 154.

An idea as to the general character of the oil produced in the United States can be gained from the following table:

 TABLE 74.—ESTIMATED AVERAGE SPECIFIC GRAVITY OF CRUDE PETROLEUM (WEIGHTED FOR PRODUCTION) BY MAJOR FIELDS¹

Field	Specific gravity	Degrees A. P. I.
Appalachian.....	0.820	41.0
Lima-Indiana.....	0.845	36.0
Illinois and southwest Indiana.....	0.863	32.5
Mid-Continent.....	0.850	35.0
Gulf Coast.....	0.919	32.5
Rocky Mountain.....	0.837	37.5
California.....	0.896	26.5

¹ U. S Mineral Resources, 1923, Part 2, p. 421.

Color.—The color of crude petroleum varies widely. It may be reddish brown, yellow, green, or black. Some very light oils are almost colorless, or only a pale yellow like vinegar, as those in the Rattlesnake field in northwestern New Mexico. By transmitted light, the color of oils is much the same but of somewhat lighter shades. Crude oils nearly always have a greenish tinge by reflected light.

Optical Activity.—When polarized light is passed through petroleum, the plane is rotated to the right or left. Investigators have voiced the opinion that this property is not possessed by oils of inorganic origin but is well marked in those derived from organic matter.¹ If this is universally true, optical activity becomes very strong evidence for the organic origin of petroleum.

This optical activity has been shown to be due to cholesterin (of animal origin) and phytosterin (of vegetable origin). These compounds are derived from the decomposition of protein. Small amounts of them are present in essentially all oils, and their presence is of much significance in deciding between an organic and an inorganic origin for petroleum.

Boiling Point.—The boiling point of crude petroleum ranges from 74, in some Pennsylvania oils, to 170°C. for an oil from Hanover, Germany. A very unusual oil having a boiling point but slightly above 0°C. occurs in the Rattlesnake pool in northwestern New Mexico (see below).

Solidification Point.—An oil from the Brenham salt dome, Texas, 40.32° A. P. I. (0.8235 natural scale), solidifies at 2 to 5°C. The large amount of paraffin in the oil (37° gravity) of the Texas Panhandle area causes much trouble. The paraffin congeals at 10 to 13°C. and must be heated to 60 or 63°C. to be melted. Steam and hot water are used to melt it. The temperature at the bottom of the wells is 35°C.

NATURAL GAS

Natural gas consists principally of *marsh gas* or *methane*, CH_4 ; small amounts of *ethane*, C_2H_6 , *carbon dioxide*, CO_2 , and nitrogen, N_2 ; and, rarely, *propane*, C_3H_8 , butane, C_4H_{10} , and heavier hydrocarbons. Rarely also, the valuable gas *helium* is present in certain mid-continental gas fields.

Physical Properties.—Natural gas is colorless and odorless and, unlike coal gas, is not dangerous for man to breathe until there is about 60 per cent of it in the air. Amounts, however, as small as 5 to 12 per cent when mixed with air produce a dangerous explosive.

Methane and Ethane as Constituents.—Methane is the dominant constituent of essentially all natural gases, in amounts ranging from 50 to 98 per cent. Ethane is much less common but is a very desirable

¹ CLARKE, F. W., Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, p. 753, 1924.
BACON and HAMOR, "The American Petroleum Industry," vol. I, p. 114, 1916.
BROOKS, B. T., "The Non-benzenoid Hydrocarbons," p. 31, 1922.

constituent because it increases the heating power of gas. The heating power of a gas from Barren County, Kentucky, containing 69.7 per cent ethane, is 1,548 B. t. u. per cubic foot. This is a one-third greater heating power than is possessed by the average gas containing over 90 per cent methane.

The Higher Hydrocarbons as Constituents.—A gas remarkable for its high percentages of the higher hydrocarbons, propane, butane, and others, is found in the Rattlesnake field in northwestern New Mexico. This gas has the following composition:

	Percentage
Methane.....	9.83
Ethane.....	27.58
Propane.....	41.57
Butane + higher hydrocarbons.....	19.70
Nitrogen.....	1.14
Oxygen.....	0.18
	100.00

Over 61 per cent of this gas is composed of the hydrocarbons above and including propane. The associated oil, as it comes from the well, is a light amber color and has a gravity of approximately 74° A. P. I. The butane and higher hydrocarbons are liquid while in the well, as the pressure they are under is over 275 pounds (their critical pressure). As soon as the oil reaches the surface, it begins to boil vigorously though having a temperature of about 0°C. The butane is thus liberated as a gas, and, as a result, the gravity of the oil falls to 63° A. P. I.

The Rare Gases in Natural Gas. *Nitrogen.*—Few natural gases contain more than very small amounts of nitrogen. Notable exceptions are those gases containing helium, some of which are dominantly nitrogen, and in all of which the nitrogen content is high. The composition of some gases high in nitrogen is given in Table 75.

Helium.—Traces of helium are found in most of the natural gas of the eastern and central parts of the United States, but gas containing more than 0.5 per cent is found only in three localities. One of these is in southern Kansas and northern Oklahoma, another in north-central Texas, and the third in Potter County in the Texas Panhandle. In the Kansas-Oklahoma area, the richest gas occurs in the vicinity of Dexter in Cowley County, Kansas, and in a newly discovered gas pool near Moline, Elk County, Kansas. The helium content of the former was as high as 1.93 per cent, and the latter is reported to contain 3.4 per cent helium. The government extraction plant at Fort Worth, Texas, gets its natural gas from the Petrolia field in Clay County, near the northern boundary of Texas. A newly discovered field in Potter County, Texas, 12 miles from Amarillo, produces a gas having 1.75 per cent helium. The government has secured leases on this field and is erecting a plant at

Amarillo for the purpose of extracting the helium. The helium content of the gas of the Petrolia field is steadily declining; and, as the new government airships being built will each require 6,000,000 cubic feet of this non-inflammable gas, an adequate source is needed for their use. The following table gives the composition of some helium-bearing gases:

TABLE 75.—THE COMPOSITION OF SOME HELIUM-BEARING, NITROGEN-RICH GASES

Field and location	Methane, CH ₄	Ethane, C ₂ H ₆	Carbon dioxide, CO ₂	Nitrogen, N	Helium, He	Oxygen, O ₂
Petrolia field, Clay County, Tex. ¹ ...	50.60	10.90	0.10	37.45	0.945	
Dexter, Cowley County, Kans. ² ..	14.85	0.41	....	82.70	1.840	0.20
Eureka, Greenwood County, Kans. ² ..	51.80	.....	0.20	46.40	1.500	0.10
Westbrook field, Mitchell County, Tex. ³	5.60	1.10	0.10	93.20		

¹ Analysis by C. W. Seibel, U. S. Geol. Survey *Prof. Paper* 121, p. 39.

² Analyses by Cady and McFarland, U. S. Geol. Survey *Prof. Paper* 121, p. 39.

³ Analysis made for *Oil Weekly*, A. A. P. G. *Bull.*, vol. XI, p. 474, 1927.

Carbon Dioxide.—A gas consisting dominantly of carbon dioxide was found in a well, 5,100 feet deep, in northwestern Colorado. The well produced about 500 barrels of oil and 20,000 cubic feet of gas per day. The carbon dioxide expanded as it neared the surface and lowered the temperature of the oil to about -43°C . (-135°F .). The lead line from the well was covered with several inches of ice, and the oil, which was like vinegar in color, rattled along the pipe in chunks. A gas that contained 30 per cent carbon dioxide was obtained from a well in the McKittrick field in California.

Source of the Rare Gases.—The source of these rare gases constitutes a problem for which no adequate explanation has been suggested.

Light Oils in Natural Gas.—In recent years, it has been found that natural gas contains some light oils, which can readily be extracted and which form an excellent grade of gasoline, known as *natural-gas gasoline* or *casing-head gasoline*. About 1 gallon of gasoline is obtained from 1,000 cubic feet of gas, although the average for the gas of some fields (notably those of Oklahoma) may be double this amount. In 1927, over 1,641,144,000 gallons of this gasoline was recovered by the treatment of natural gas. The major part (83 per cent) of this production came from Oklahoma, California, and Texas.

A Comparison of Natural Gas with Commercial Gas.—It is of interest to compare the composition and heating power of natural gases with

similar facts about the common artificial gases. Table 76 gives some typical analyses and calorific values of natural gases, and Table 77 gives the same facts for the common artificial gases.

TABLE 76.—TYPICAL ANALYSES AND CALORIFIC VALUES OF NATURAL GAS FROM VARIOUS WELLS IN THE UNITED STATES

Locality of well	H ₂	CH ₄	C ₂ H ₆	CO	CO ₂	N ₂	O ₂	Heavy hydrocarbons	B.t.u. per cubic foot
Topeka, Kan.....	....	88.80	6.70	....	0.80	3.70	....	....	1,070
Louisville, Ky.....	....	77.80	20.40	....	....	1.80	....	....	1,205
Glasgow, Barren County, Ky.....	....	23.60	69.70	....	2.50	1.30	....	....	1,548
Cincinnati, Ohio.....	....	96.50	....	....	....	2.10	....	....	1,028
Findlay, Ohio.....	1.64	93.35	....	0.41	0.25	3.41	0.39	0.35	1,011
Oil City, Pa.....	....	67.60	31.30	....	....	1.10	....	....	1,302
St. Ive, Pa.....	6.10	75.54	....	trace	0.34	....	....	18.12	1,117
Pittsburgh, Pa.....	9.64	57.85	....	1.00	....	23.41	2.10	6.00	748
Titusville, Crawford County, Pa.....	....	6.60	91.10	....	....	2.30	....	....	1,765
Anderson, Ind.....	1.85	93.07	....	0.73	0.26	3.02	0.42	0.47	1,017
Pawhuska, Okla.....	....	88.60	5.60	....	1.40	4.40	....	....	1,048
Nowata, Okla.....	....	95.20	....	....	1.30	3.50	....	....	1,014
Fort Worth, Tex.....	....	51.50	10.20	....	....	38.30	....	....	738
Corsicana, Tex.....	....	98.00	....	....	0.70	1.30	....	....	1,044
Midway, Calif.....	....	85.70	5.70	0.50	5.60	....	1.70	....	1,037
McKittrick field, California.....	....	66.20	1.00	....	30.40	2.40	....	....	724

TABLE 77.—AVERAGE COMPOSITION AND HEATING POWER OF COMMERCIAL GASES¹

Kind of gas	Illuminating gases	CO	H ₂	CH ₄	C ₂ H ₆	CO ₂	O ₂	N ₂	B.t.u. per cubic foot
Blau.....	51.9	0.1	2.7	44.1	...	....	...	1.2	1,704
Oil.....	31.3	2.4	13.5	46.5	3.9	0.3	...	1.1	1,320
Pintsch.....	30.0	0.1	13.2	45.0	9.0	0.2	...	1.6	1,276
Oil water.....	7.0	9.2	39.8	34.6	...	2.6	0.2	6.6	680
Carbureted water.....	13.3	30.4	37.7	10.0	3.2	3.0	0.4	2.1	643
Coal.....	4.0	8.5	49.8	29.5	3.2	1.6	0.4	3.2	622
Wood (pine).....	10.6	27.1	32.7	21.5	...	4.9	0.4	2.6	607
Blue water.....	....	40.9	50.8	0.2	...	3.4	0.9	3.5	299
Producer (coal).....	0.2	17.6	10.4	6.3	...	7.8	0.7	58.1	161
Producer (coke).....	....	25.3	13.2	0.4	...	5.4	0.6	55.2	137
Blast furnace.....	....	26.5	3.5	0.2	...	12.8	0.1	56.9	100

¹ Brooks, B. T., "The Chemistry of the Non-benzenoid Hydrocarbons," p. 40, 1922.

Some of these commercial gases have a higher thermal efficiency than natural gas; but, aside from oil gas, none is extensively used for lighting and heating purposes. Natural gas is the nearest approach to an ideal gas fuel.

ORIGIN OF OIL AND GAS

The origin of petroleum was formerly one of the much disputed problems of geology, but in recent years most men have come to accept one view. It cannot be said, however, that the details of the process of oil formation are understood much better now than formerly. The origin of petroleum involves the origin of gas and of asphaltic materials, as these products are not only found associated with petroleum but also can be produced from it by artificial means.

The first studies of petroleum were chemical determinations of its composition, and therefore chemists were the first to advance theories for its origin. Various hydrocarbon compounds were prepared in the laboratory from inorganic constituents; and, as some of these compounds resembled petroleum, a theory based on the laboratory work was advanced to account for the formation of oil. Such theories were presented by Berthelot (1866) and by Mendeléeff (1877) and, carrying with them the authority of these two great chemists, were rapidly adopted by others. Chemists have been, therefore, the chief supporters of the inorganic theory. The theory, however, when applied to petroleum and its occurrence, is based on pure assumption. Chemists were able to produce products similar to petroleum from organic materials as well as inorganic, and so it seems strange that it was so long before they regarded favorably the organic view of origin.

Geologists, through their studies of the occurrence of petroleum, early recognized the possibility and probability of an organic origin for oil and have long advocated such a view. Considerable data have been added to the problem by careful field studies in recent years and by the synthetic studies of Engler, Warren and Storer, Day, Höfer, Potonie, and many others who have been able to produce various hydrocarbons from animal and vegetable materials. The organic origin of petroleum is now the prevalent view, yet a statement of belief is far from being an explanation of the detailed processes by which organic compounds are converted into the myriads of compounds in petroleum, natural gas, and the solid hydrocarbons. Contributions to the solution of the problem are occasionally made, only to be subjected, in turn, to the tests of time. The parts found applicable are saved, the others are discarded.

THE INORGANIC THEORY OF THE ORIGIN OF OIL

The experiments proving that hydrocarbons similar to those found in petroleum could be made from inorganic materials were carried on during the middle of the last century.

The Alkaline-metal Theory.—Daubréé, an eminent French geologist of the period, in discussing the interior of the earth, suggested that it might contain the alkaline metals, sodium, potassium, and lithium. Although this was a pure assumption, Berthelot, a French chemist, having proved (1866) that carbon dioxide would react with these alkaline metals at high temperatures and produce acetylides, suggested that these might form within the earth and later react with water to form acetylene. In turn, the different hydrocarbons could be built up through the polymerization of this gas. Three molecules of acetylene, C_2H_2 , would unite to form one of benzene, C_6H_6 . The absolute lack of any evidence to prove the presence of such metals within the earth leaves this theory a mere assumption. It is widely quoted, however.

The Carbide Theory.—It was Mendeléeff who advanced the carbide theory. Presupposing the presence of iron carbides within the earth, he suggested that water percolating downward and coming in contact with the carbides would generate acetylene, which later would be converted into the higher hydrocarbons. He suggested "iron" carbide for the reaction, but the carbide of any other metal would have acted in the same way; in fact, aluminum carbide would yield methane, and some of the rare elements (such as cerium and uranium) would yield liquid and solid hydrocarbons.

That carbides of any kind occur within the earth has not, however, been proved. Becker¹ has suggested that the variations in the lines of magnetic declination were more irregular in the oil fields than elsewhere and that this was compatible with the carbide theory of the origin of oil, the disturbances in the magnetic lines being due to the iron released by the breaking up of the carbide in forming the hydrocarbons. Tarr² pointed out that exceptional irregularities in the magnetic lines are the result of greater detailed mapping in a given area; furthermore, that these lines shift constantly, which they would not do if they were caused by stationary masses of iron below; and, lastly, that the presence of such masses of iron would be shown by the isoclinals determined by a vertically swinging needle. The isoclinals, however, show no more marked variations in the oil fields than in adjacent areas. These facts seem to prove that masses of carbides (now iron or iron oxides) never existed below the oil fields.

The Theory of the Volcanic Origin of Petroleum.—A few men have advocated a volcanic origin for petroleum. Although it is true that hydrocarbons have been found in volcanic gases and small quantities of them in igneous rocks, the amounts are so insignificant as to render

¹ BECKER, G. F., Relations between Local Magnetic Disturbances and the Genesis of Petroleum, U. S. Geol. Survey *Bull.* 401, 1909.

² TARR, W. A., The Lack of Association of the Irregularities of the Lines of Magnetic Declination and the Petroleum Fields, *Econ. Geol.*, vol. VII, p. 647, 1912.

very unlikely a volcanic origin for oil. The hydrocarbons in volcanic gases may easily have been derived from the heating of the adjacent rocks or by reactions between the gases themselves.

Objections to Inorganic Theories.—If petroleum had originated from alkaline metals or carbides, it should be found widely distributed in *all parts* of the earth and associated with igneous, metamorphic, and sedimentary rocks. This is far from being the case. If it were of igneous origin, the volcanic areas should be sources of oil; which they are not. The fact that there is a definite association of petroleum with sedimentary rocks can be taken as further evidence, although indirect, against its inorganic origin.

THE ORGANIC THEORY OF THE ORIGIN OF OIL

The decomposition and alteration of material, originally organic, is believed to have been the method by which petroleum was produced. Many experiments have shown that both animal and vegetable materials, when subjected to distillation, yield hydrocarbons similar to those found in petroleum. Warren and Storer (1865) produced from organic materials a mixture of hydrocarbons similar to kerosene, but it was Engler's investigation of the products distilled from fish oil, made public in 1888, that marked the beginning of many important studies in synthesizing petroleum from organic substances. Later studies by Engler, Höfer, Day, and others have proved that both animal and vegetable matter will produce oil.

The Relative Significance of Plants and Animals in Oil Formation.—Investigators do not agree as to which have contributed the more to our petroleum supply, animals or plants. Probably, neither has always dominated, as there is a marked difference in the composition of petroleums in different fields, and these variations may well be due to differences in the original source materials. The asphaltic petroleum of California is held by Anderson¹ and Tolman² to have come mainly from diatoms, as they had proved that living diatoms contain drops of oil. Other men have sought to show that asphaltic oils are mainly of animal origin, but the evidence that the California oils are dominantly of vegetable origin is very conclusive. Some species of algæ, notably *Elacophylon*, are, according to Thiessen,³ rich in oil. Brooks⁴ quotes Kraemer and Spilker as saying that certain algæ contain

¹ ANDERSON, F. M., "Origin of California Petroleum," *G. S. A. Bull.*, vol. XXXVII, pp. 585-614, 1926.

² TOLMAN, C. F., "Biogenesis of Hydrocarbons by Diatoms," *Econ. Geol.*, vol. XXII, p. 454, 1927.

³ THIESSEN, R., "Origin of Boghead Coals," *U. S. Geol. Survey Prof. Paper* 132, p. 30, 1925.

⁴ BROOKS, B. T., "The Non-benzenoid Hydrocarbons," p. 30, 1922.

droplets of oil in their cells. There is no reason to think that such plants may not have contributed to our source of petroleum. The paraffin base may have had its origin in plants, or it may have been the result of the alteration which the material had undergone. Many oils are mixtures of these two classes. Experiments by Day and others have shown that crude oil filtered through clay or shale is broken up into lighter and heavier oils. If petroleum can migrate through shales or clay (which is doubtful), it is possible that the paraffin oils might be the result of such fractionation during the movement of the oil through the rocks. It seems far more probable, however, that the final differences in petroleum really had their origin in the character of the original source materials, supplemented by the possible changes which they have subsequently undergone.

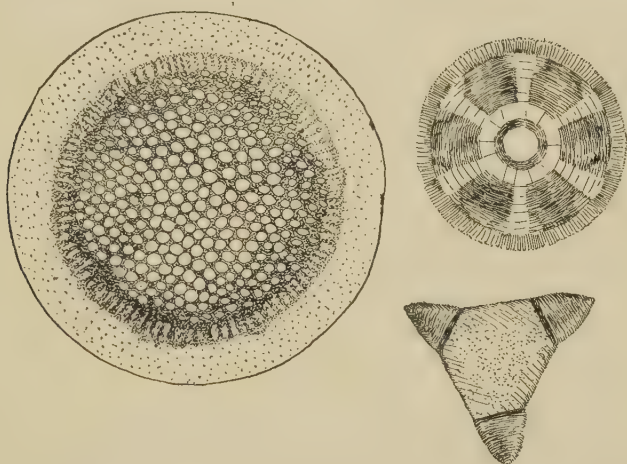


FIG. 153.—Diatoms (enlarged several hundred times) from the Monterey formation (Tertiary), California. (After Arnold and Anderson, *U. S. Geol. Survey Bull.* 322, pls. 19 and 20.)

Plants Probably the Source of More Petroleum than Animals.—When we consider all the factors, the evidence we obtain favors the view that plants were the most common source of petroleum. Many oil fields show little more than traces of animal remains. Few remains of plants are ever found on account of their perishable tissues; but, considering the relatively harder parts of animals, if many of them had gone into the formation of oil, considerable remains of them would be found. Although we may regard plants as the major source of oil, we do not exclude the idea of any possible contributions from animal sources.

The fact remains, however, that plants (in at least two groups, the diatoms—see Fig. 153—and algæ) have been proved to *contain drops of actual oil within the cells of the organism*. This oil is liberated at the death of the plant, of course, but it is possible that it may also be

freed by a change in plant environment. The latter idea has been suggested by the fact that the diatoms washed up on the shore at Copalis Beach, Washington, when placed in fresh water absorbed the water and liberated the drops of oil.¹

Just how adequate these sources might have been is not known (equally true of the other sources, however). A suggestion may be obtained from the fact that thousands of tons of diatoms were swept upon the beach in Washington during one of the "epidemics" in 1925.²

Further evidence that oil as such is set free by plants (possibly by decomposition in these cases) is the fact that it is often found in peat bogs and swamps. Dorsey³ has reported a high-grade hydrocarbon (closely akin to kerosene) in seepages in swamps south of Atlanta, Georgia.

The sources just mentioned are mainly the lower types of plants. Higher plant types having a greater abundance of cellulosic material do not appear to be important contributors to oil accumulation, yet many of them contain various hydrocarbons. These hydrocarbons would be set free only after the complete decay of the plant, but they might then be buried and give rise to kerogen shales.

Animals, of course, contain fats in their bodies, but these fats undergo chemical changes before they become oil. Since, therefore, no oil is found in animal tissue, and since so few remains of the hard parts of animal bodies exist in the oil fields, we have little direct evidence pointing toward animals as the source of oil deposits.

THREE METHODS BY WHICH OIL ORIGINATED FROM ORGANIC MATERIAL

The process by which petroleum was produced from organic material is only partially understood. The theories advanced on the subject are (1) that *the oil was formed as such by living organisms* (this has been proved in the case of diatoms and certain algæ), (2) that *it was formed during the decay of the organism by the action of certain bacteria*, and (3) that *it was due to the action of physical agents upon buried organic debris that was susceptible of being converted into liquid hydrocarbons*. Needless to say, these various theories would not have been advanced had there not been some evidence in support of each. It is generally recognized that although one of these methods of origin predominated for the oil of a field, the other methods may have been operative also, in some degree.

¹ BECKING, TOLMAN, McMILLIN, FIELD, and HASHIMOTO, Preliminary Statement regarding the Diatom "Epidemics" at Copalis Beach, Washington, and an Analysis of Diatom Oil, *Econ. Geol.*, vol. XXII, pp. 356-368, 1927.

² BECKING, L. B. and others, *idem.*, p. 362.

³ DORSEY, G. E., Present Status of Carbon Ratio Theory, *A. A. P. G. Bull.*, vol. XII, p. 467, 1927.

1. **Petroleum Formed as Such by Living Organisms.**—There is much to be said in favor of the idea that the organism itself actually produced the original drop of oil. Numerous hydrocarbons are segregated by various plants, so that the presence of a drop of liquid hydrocarbon within the cells of plants is the rule rather than the exception. If organisms that segregated such drops of oil developed in great numbers, they would become a potential source of petroleum, provided the drops were not lost. Thus, we have here a natural means by which oil may have been produced, without any recourse to subsequent biochemical or geochemical agencies, about which we must theorize so extensively. Having learned that such plants as the diatoms and algæ may liberate drops of oil, we turn our attention to accounting for the burial of the oil with the sediments and the subsequent oil accumulation.

Burial of the Oil Drops.—The droplet of oil might have been liberated from the organism while it floated in the water or after it had settled to the sea bottom. In order that the oil might be saved, it had to be buried on the bottom. The only way of accomplishing burial is by loading the drop of oil with something having a higher specific gravity than water. Stuart,¹ some years ago, suggested the ideal agent, *i.e.*, mud. He found, as have others, that oil mixed with mud settled to the bottom. Stuart determined that 23.5 cubic centimeters of mud carried down about 14 cubic centimeters of oil and that 10 cubic centimeters of a certain light American oil went down with 10 cubic centimeters of clay. These figures represent maximum amounts, and it is improbable, of course, that any natural mud would contain such quantities of crude oil. In fact, it has been found² that, if a ratio of 1 cubic centimeter of oil to 15 or 20 cubic centimeters of clay is used, essentially all of the oil is carried to the bottom with the clay. The union of oil with the clay, in these experiments, was most complete when the amount of water was large, *i.e.*, 2,500 cubic centimeters to 20 cubic centimeters of clay. Extremely fine clay did not remove the oil from the water. These experiments indicate that the small amount of mud (if not too fine) in the sea water along the shore would be an ideal condition for burial of oil drops.

Needless to say, if the decomposition of the organism occurred on the floor of the body of water, the oil drops were already associated with mud and probably would have become entangled and buried in place. Those particles freed above in the water, or having escaped from the bottom, would have had to come in contact with mud in order to become preserved. Burial might have been accomplished by the union of the oil with colloids in the mud. Especially might this have been true if

¹ STUART, MURRAY, The Sedimentary Deposition of Oil, Geol. Survey India *Records*, vol. XL, Part 4, pp. 320-333, 1910. Review by David White, *Econ. Geol.*, vol. VII, pp. 91-95, 1912.

² Experiments conducted for the author at the University of Missouri.

the particles of each material carried opposite charges of electricity. Once enmeshed in the mud, the oil drops may have been buried or, through migration, may have found their way out of the mud into a porous rock.

The view that the oil droplet became entangled and buried in mud on the bottom of the body of water accounts for the dominant association of petroleum with near-shore deposits, as muds are most abundant near shore, the amount of life is greater there than elsewhere, and porous deposits (such as sands) are most apt to occur there. The association of oil with near-shore deposits is favorable evidence for the view that the oil was buried, as such, and is also in accord with any theory of subsequent distillation from material buried in the same shales.

Migration of the Oil Particles.—As the muds compacted, the globules of oil buried in them would have become compressed and distorted. If other globules were near, they may have been forced to unite. Where the interstices in the mud were capillary in size, the associated water would have displaced the oil in large part, because of its greater surface tension in capillary openings. The oil would thus have been forced out (dominantly upward, but also downward) into the larger openings. As the accumulation of sediments and their compaction continued, a constant migration of the oil would have taken place. If a porous rock occurred below the oil-bearing strata, a certain amount of oil might have migrated into it. The most common direction of movement, however, would have been upward, and this movement would have continued until a porous deposit (a bed of sandstone or sandy shale) capped by an impervious layer was reached. The upward-moving oil would then have entered the porous bed which thus became a reservoir for the oil. Lateral migration into porous rocks would have been possible, also.

The migration and consequent accumulation of the oil drops would have been influenced by the rate of compaction of the sediments, the amount of water in them, their coarseness, the amount of oil present, and many other factors. Migration, however, might not have taken place until long after burial. The possibilities involved in burial and subsequent migration are so many that dogmatism is out of place in discussing them.

2. The Formation of Oil by Bacterial Decomposition of Organic Material.—The second way by which petroleum may have originated from organic material is its formation, either from plants or animals, by means of bacterial decomposition. This process must have taken place in water (some maintain that it must have been salt water, but this does not appear essential), because decomposition with complete exposure to air would have resulted in the loss of all alteration products. The organic material may have been any type of animal (almost all types living in water, from the foraminifera to the vertebrates, have been

suggested) or any type of plant, though oil-forming plants are confined largely to the lower forms, especially diatoms, algæ, and seaweeds.

Results of Bacterial Action.—The anærobic bacteria broke up the organic material in order to secure oxygen for their life processes. With the removal of the oxygen from the tissues attacked, the carbon and hydrogen were freed. Some carbon and hydrogen united to form the very stable methane, CH_4 , and related compounds, and some may have united to form oil. Other parts of the organism, such as fats, waxes, and related compounds, being very resistant materials, did not readily succumb to attack by bacteria or by the solutions found in the rocks containing organic remains. As a result, these parts were concentrated as the other parts were removed.

Burial.—The residual fats and waxes were buried in place on the sea floor. Any oil formed may have been so buried or may have been transported before burial. In any case, mud was the agent that accomplished the burial of all the materials. Silts contain essentially no organic material.

The increasing production of oil from limestones has raised the question as to the efficiency of limestones or calcareous muds as source rocks for petroleum. Trask¹ determined the bituminous content of many calcareous muds and found only two that contained important amounts, and these two yielded only 2.5 gallons of oil per ton of limy oozes. Off-shore deposits, he found to be very low in organic material. He concluded that most limy oozes are not potential sources of oil but that some might be. There are a number of reasons for this fact. First, most limestones are off-shore deposits, which, as Trask has shown, are improbable sources of oil. Second, even though a limestone is dominantly organic in origin, its purity is evidence that the tissues of the organisms which formed it had been destroyed before the burial of the shells. Third, the process of crystallization, which all limestones undergo, would aid in eliminating the organic matter, although a small amount is retained, as is shown by the gray color of many limestones. Fourth, evidence is being constantly collected which shows that limestones of chemical origin are more abundant than has been generally believed. Even the chalk of England, long regarded as wholly organic, has been shown to be composed dominantly of a chemically formed material containing only minor quantities of organic remains.² The studies which have been made of American chalks indicate a similar origin.

¹ TRASK, P. D., Limestones as a Source of Oil, *A. A. P. G. Bull.*, vol. XII, p. 556, 1928.

—, Results of Distillation and Other Studies of the Organic Nature of Some Modern Sediments, *idem*, vol. XI, p. 1221, 1927.

—, The Potential Value of Several Recent American Coastal and Inland Deposits as Future Source Beds of Petroleum, *idem*, vol. XII, p. 1057, 1928.

² TARR, W. A., Is the Chalk a Chemical Deposit? *Geol. Mag.*, vol. LXII, pp. 252–264, 1925.

Carbonaceous rocks vary widely in the amount of bituminous *débris* which they contain, and the material itself has a wide range in composition (from essentially inert carbon to high-grade hydrocarbons). These variations were occasioned by the character of the original organic material, the degree of its decomposition, and the amount of sorting which it has undergone.

Processes Subsequent to Burial.—The oil formed by bacterial decomposition of the organic material had the same history of migration and accumulation as that described for the oil drops under method 1. The buried fats, waxes, and related compounds were potential sources of oil; and if, as is not improbable, the action of the anærobic bacteria could continue for long periods of time after burial, oil might be produced from them. Bastin¹ has shown that sulfate-reducing bacteria exist at depths of 3,000 feet, so it seems not improbable that other anærobic bacteria might exist at similar or even greater depths. It is also possible that this buried organic material might be converted into oil and gas by physical agents. This is discussed under method 3.

3. Possible Formation of Oil through Action of Physical Agents on Organic Material.—The method of accounting for the origin of petroleum through the action of physical agents upon buried organic *débris* is known as the “dynamochemical method.” *Pressure* and *heat* are thought to be the agents which converted the organic residue into petroleum.

Sources of the Pressure.—The source of the pressure was twofold: (1) *that which arose from the weight of the overlying sediments* (totaling thousands of feet in some areas) and (2) *that which resulted from diastrophic movements*. These movements ranged in the intensity of their effects from the production of small local warpings and folds to the formation of mountains. Evidence, more or less convincing, has been cited in support of each of these methods as the source of the pressure.

Sources of the Heat.—The heat was *due* (1) *to the pressure caused by deep burial* [a temperature of 77°C. (170°F.) has been reported from a depth of 8,300 feet in Reagan County, Texas], (2) *to the pressure caused by diastrophic movements*, and (3) *to intruded igneous rocks*.

The Plausibility of the Heat and Pressure Theory.—Heat and pressure are believed by many men to have been effective in breaking up the buried hydrocarbons (called “kerogen” by some) into petroleum. Heat due to igneous rocks can be ignored, save possibly in a few instances (the Panuco field, Mexico, for example²), for igneous rocks are generally absent from oil fields. It is unlikely, moreover, that the heat due to the pressure developed by deep burial or by earth movements ever reached temperatures necessary to distil oil from organic matter in rocks. Arti-

¹ BASTIN and collaborators, *A. A. P. G. Bull.*, vol. X, p. 1270, 1926.

² BAKER, C. L., Panuco Oil Field, Mexico, *A. A. P. G. Bull.*, vol. XII, pp. 395–441, 1928.

ficial distillation requires a temperature from 350°C. upward, and all the evidence in oil fields is opposed to the likelihood of temperatures' being that high. The author of this book believes that heat has been of only minor significance in the formation of oil.¹

A number of men have subjected oil shales and muds containing oil to high pressures in the effort to prove that pressure was important in the formation of oil, but only negative results were obtained.

That heat and pressure might be effective in producing petroleum under special conditions is possible, but the degree to which they have been effective can be determined only by much more research than has been put upon the problem to date (1929). The relatively shallow oil sands occurring in quite undisturbed sediments in the central part of the United States are certainly evidence against the view that either heat or pressure is very effective in oil formation.

SUMMARY

The organic theory as to the origin of petroleum is strongly supported by many lines of evidence. Some of these proofs are: the association of oil only with sedimentary rocks that show evidences of organic matter; the association of these rocks with deposits that show that they were laid down near shore (the place where organisms live in greatest abundance in any body of water); the presence in petroleum of phytosterin (a plant derivative) and cholesterin (an animal derivative); the optical activity of petroleum; and the presence in plants not only of fats and resins but also of actual droplets of oil and in animals of fatty compounds capable of being converted into the various hydrocarbons of petroleum.

The majority of investigators are undoubtedly agreed as to the organic source of petroleum. There is little agreement, however, as to the biological and chemical processes which took place in producing the petroleum. We have strong evidence as to the source of oil; and, in our pools, we have the final product. The intervening events are hidden. The proper evaluation of the various theories that have been advanced must yet be made.

ORIGIN OF GAS

Natural gas, as already stated, consists dominantly of methane. It also contains small amounts of ethane. Methane is the most easily formed and the most stable gas of the entire series of petroleum hydrocarbons. It is formed abundantly by bacterial action in swamps and bogs and also on the sea floor, in which case it might be buried in the muds. Methane (called "fire damp" by the miners because it is so

¹ In a recent paper, W. L. Russell has emphasized the same point. A. A. P. G. *Bull.*, vol. XIII, pp. 75-83, 1929.

explosive) is found in coal mines, as it was formed during the development of the coal. It can also be formed from buried oil or organic matter by simple chemical reactions, whereby the unsaturated hydrocarbons give rise to the saturated compound methane. The development of the numerous, heavy, more or less oxygenated hydrocarbons (of which the asphalts are common examples) would probably also mean the production of some methane.

Heat may be a possible factor in the formation of gas, though it is probably not important at all. The temperature of the rocks in the oil and gas fields probably never exceeds 200°C., and it is usually below 100°C. The gas formed from coal in a retort is richest in methane at 600 to 800°C., and the average coal gas contains only about 30 per cent methane.

Natural gas seems to be best explained as being due to (1) *anaerobic bacterial action* (much of the gas thus formed is lost before it can be buried), and (2) *chemical readjustments within the solid and liquid hydrocarbons* in the rocks. If the gas was formed within the rocks, its concentration into large gas pools is easier to explain than the similar concentration of oil, because, being a gas, its limitations as to movements are much less.

MIGRATION AND ACCUMULATION OF PETROLEUM

Small quantities of petroleum scattered through a rock are of no value, as it is not possible to extract them. T. Sterry Hunt has estimated that a limestone, 35 feet thick, occurring near Chicago contains 7,743,745 barrels of oil to each square mile, yet not a barrel can be extracted. The enormous accumulations, known as oil pools or fields, are the result of the *lateral* and *vertical* migration of the scattered oil drops into reservoir rocks.

It should be noted that some men do not accept the theory of migration. There seems to be, however, no logical reason why oil should not have migrated laterally for 1 mile or 20 miles if the conditions were favorable. Oil has, of course, a higher viscosity than water, but the difference is not sufficient to stop migration entirely, and water may migrate hundreds of miles. Some of our high-grade crude oils flow like vinegar, and such an oil might easily move through a sandstone for 50 miles. The most ideal source for oil would, furthermore, probably prove inadequate in accounting for most of our enormous pools unless considerable migration had taken place. Several men have recently expressed themselves strongly in favor of the idea of lateral migration.¹ Although the

¹ WILSON, W. B., Geology of the Glenn Pool of Oklahoma, A. A. P. G. Bull. vol. XI, pp. 1055-1065, 1927.

THOMAS, C. R., Flank Production of the Nemaha Mountains (Granite Ridge), Kansas, *idem.*, pp. 928, 929.

problems involved in accumulation are numerous and are not as yet entirely solved, a study of many productive fields has given a fairly clear outline of the process. These studies have been carried on because a knowledge of the method of migration is of value in locating new oil pools.

MIGRATION

The causes of migration are (1) *gravity*, (2) *compaction*, (3) *crystallization*, (4) *cementation*, (5) *capillarity*, (6) *differences in specific gravity of oil and water*, (7) *movements of associated water* (hydraulic theory) and gas.

Gravity.—The force of gravity acting on oil has been of slight importance in causing the movement of oil through rocks, because of the friction encountered. If, however, the reservoir rock was in a position favoring vertical movement, oil, if unassociated with water, would have moved down into the lowest part.

Compaction.—The consolidation of the sedimentary rocks enclosing the oil was due to the weight of the overlying beds. It was accomplished by forcing out the water, which brought the constituent rock particles closer together. As long as the openings between the particles were supercapillary in size, this process undoubtedly aided the migration of the oil by forcing it along with the water into the larger spaces. Compaction would have been especially instrumental in shifting the scattered droplets of buried oil, causing their accumulation in porous parts of the rock.

Crystallization.—Crystallization was a factor only in limestones and dolomites. While the calcareous oozes were crystallizing, any liquid contained in them would have been forced out along with the water. Solid particles, and, less frequently, the liquid particles might have been enclosed in the growing crystal. (Specimens of calcite enclosing drops of petroleum have been obtained from wells in Mexico.) In the main, however, crystallization would have aided in pushing the oil out into the larger pore spaces. Aside from this local first push, crystallization would not have been a factor in any subsequent movement.

Cementation.—Cementation may take place in any rock that mineral-bearing solutions can enter. The carbonate cements are the most common ones, but silica and iron oxides are deposited locally. Cements fill up the interstices of the rock and thereby cause any oil present either to migrate or be sealed in. The movement, however, would be small, unless cementation was extensive.

Capillarity.—Considerable attention has been given to capillarity as a factor in the movement of oil. Capillary openings are dominantly flat or round. A tabular opening ranges from 0.254 to 0.0001 millimeter in width, and a round opening from 0.508 to 0.002 millimeter in diameter. Openings larger than these are supercapillary, and smaller are subcapillary. The movement of any liquid through a capillary opening

is due to the surface tension of the liquid; oil will move through dry clay because of this. The capillary movement of oil, however, is not by itself a very important factor in migration; but, when the oil is associated with water, the relative ability of oil and water to occupy a capillary space becomes effective. Water has a much greater surface tension than oil; hence is capable of displacing it in a capillary opening. The whole tendency, therefore, is to force the oil out of the smaller spaces into the larger openings, where it will be able to move more freely because of less friction. Although the water may force the oil out of capillary openings, it is not effective in causing any movement in supercapillary openings. Like some of the factors given above, capillarity is mainly effective in getting the oil out of the fine-grained shales, sandstones, and limestones where the openings are so small that there is no movement of the petroleum. It is especially effective in shales, because in them most of the openings are capillary and subcapillary and, also, because shales are the chief sources of petroleum.

Differences in Specific Gravity of Oil and Water.—Water, oil, and gas are common associates in oil fields. Gas occurs in widely varying amounts, but few fields are entirely free from it. Water is usually present, also, but in some pools it is absent. When oil, gas, and water are associated, their differences in specific gravity greatly aid in the migration of the oil. Fresh water has a specific gravity of 1. Salt water (the usual type of water associated with oil) has a specific gravity ranging from 1.0023 in water containing a small quantity of salt to 1.0227 in water with large quantities of salt. Oil has a specific gravity range of 0.690 to 0.996. Natural gas is lighter than air. If oil, gas, and water were all present in a rock and free to move, they would arrange themselves in layers, the water below, the oil next, and the gas on top. This would be brought about because a drop of oil entering an underground body of water would soon migrate upward through the water because of its lower specific gravity or buoyancy. Gas would do the same. A segregation, therefore, of water, oil, and gas would be brought about by differences in specific gravity alone. It is difficult to believe that this easy means of segregation and movement has not been an extremely common factor in causing a lateral migration. It may well have been the most effective cause of oil migration.

Movement of Associated Water and Gas.—Undoubtedly, any movement of the water associated with the oil and gas would mean some movement of those substances also. Laboratory experiments have shown that water is effective in displacing oil; and flooding of wells that had ceased to flow has resulted in renewed life of the wells. Movement of gas through the oil would also aid in causing oil migration.

The idea that moving water (and gas) was largely responsible for the migration of petroleum was advanced by Munn and called by him

the hydraulic theory.¹ He maintains that the differences in specific gravity are inadequate to account for the amount of movement oil has undergone and suggests that the shifting of the oil was due to the water moving through the rocks. In the first place, Munn's assumed porosities of the various rocks (they must be porous to permit the circulation of the water) are certainly too high. Shales are universally regarded as suitable cap rocks not only for oil *but also for water and gas*, yet Munn states that "their pore space undoubtedly ranges from 1 to 15 per cent with an average of not less than 6 per cent." Shales, however, *are impervious* to oil, water, and gas, as just noted. Furthermore, the distribution of water, oil, and gas in thousands of pools proves that there is *not* an active circulation of the water associated with the oil and gas. All these materials are in a static condition in oil pools (save for the shifting due to differences in buoyancy), until they are disturbed by the drill. Some years ago, a series of experiments was conducted at the University of Missouri on removing oil from sands by water under pressure. The results showed that when the water could and did break through the oil-saturated portion it thereafter followed its self-made channels through the oil instead of displacing it. This explains, in part at least, why, when a well has started to flow water, it continues to do so. The moving water, assumed by Munn's theory, would likewise follow its accustomed path, instead of displacing any appreciable amounts of oil. Munn's theory may be applicable in some degree to certain pools, but it has no general application.

There is a generally accepted view that the water associated with oil and gas has undergone considerable movement. That such a concept is true can be questioned. If the oil and gas were confined to a specific bed, the water was, also, and its movements were restricted to the reservoir rocks. So the difficult questions that must be answered are: what could have caused the water to move about in the reservoir; and, if it was moving, where was it going? The composition of the water within a single reservoir is remarkably uniform and, in some cases, approximates that of sea water, showing that it is a connate water. Such waters have been confined since burial and certainly have not mingled with other waters. Lilley has called attention to the fact that the waters of different horizons in the same field are markedly dissimilar, showing that there is *not* an active circulation between the different horizons. In short, all the evidence indicates that there has been a minimum amount of movement of the water associated with the oil and gas of the reservoirs and of that of the adjacent water horizons. Any movement of the water, oil, and gas has been largely in connection with the segregation of each material and with porosity changes. Earth movements causing faulting

¹ MUNN, M. J., The Anticlinal and Hydraulic Theories of Oil and Gas Accumulation, *Econ. Geol.*, vol. IV, pp. 509-529, 1909.

and folding would markedly derange the adjusted water conditions, but water movements in such disturbed areas do not appear to have been any more effective in causing an accumulation of oil than those in undisturbed areas.

Summary.—Stages in the migration of petroleum were (1) its removal (by compaction, crystallization, or capillary force) from the original mud in which it was buried or in which it was formed through dynamochemical changes, and (2) its lateral and vertical migration due to differences in the specific gravity of the oil and water aided possibly by minor movements of the water and gas associated with the oil. Movement did not cease until the three substances, water, oil, and gas, had become segregated within the storage place.

ACCUMULATION

The result of the migration of oil from scattered sources to some central point is, as before noted, an accumulation of oil, which is called an "oil pool." The three conditions necessary for accumulation to take place are (1) *a reservoir rock*, (2) *a cap or retainer rock*, and (3) *a suitable position and shape of the reservoir rock*.

RESERVOIR ROCK

Any rock having a sufficiently high porosity may serve as a reservoir for the accumulation of oil and gas. The most common one is sandstone (commonly called "sand" in the oil fields). Others are limestone, dolomite, shale, and, in some pools in Texas, a porous igneous rock. A fundamental requirement of a reservoir rock is that the openings be connected with each other in order to permit the free entry and exit of the oil. Dolomite has a porosity of 12 to 14 per cent, but the openings in it are not connected. A high porosity does not necessarily mean, therefore, that the rock possessing it is suitable for holding oil. Also, a rock may be unsuitable as a reservoir because the pores are so small that extraction of the oil is an impossibility. An average porosity of 15 per cent is generally used in computing possible production from oil sands.

Sandstone as a Reservoir Rock.—Sandstones show a wide range in texture and porosity. Very fine-grained sandstones (grains less than 0.15 millimeter in diameter, which is the minimum size for rounding by wind) are rarely of value as reservoir rocks. The sand in the Midway-Sunset field in California is extraordinarily fine. In a large number of samples of this sand, more than half the grains had a diameter of less than 0.147 millimeter. Most oil sands, however, are medium or coarse grained.

The shape of the sand grains is important. Perfectly rounded grains of uniform size give a maximum porosity. If the grains are rounded

but not well sorted, the pore space is greatly reduced because the fine grains lie between the large ones (see Fig. 154 *B*). Likewise, sharply angular but unsorted grains pack closely, and sorted angular grains give rise to a high porosity.

Other factors besides shape or size of the grains cause marked variations in porosity. Cementing materials are especially apt to cause a decrease in porosity (Fig. 154 *D*). Calcium carbonate, silica, and iron oxides are the most important cements. The irregular distribution of these cements (as well as differences in texture) causes marked variations in the productivity of a sand within a pool. Not infrequently, a dry hole occurs in the midst of productive wells. Clay is present in many sandstones and reduces the pore space just as does a cement.

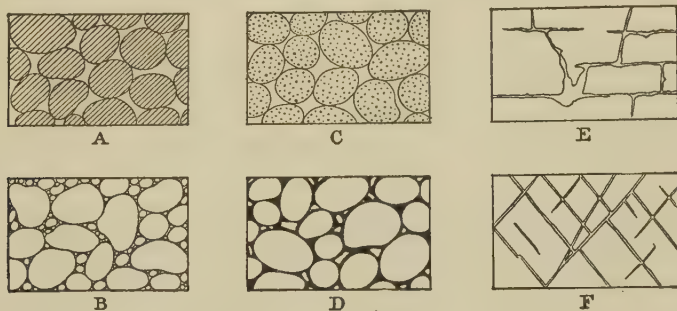


Fig. 154.—Diagram showing several types of rock interstices and the relation of rock texture to porosity. A, well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; D, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; E, rock rendered porous by solution; F, rock rendered porous by fracturing. (After Meinzer, *U. S. Geol. Survey Bull.* 489, p. 3.)

Limestone and Dolomite as Reservoirs.—In a surprisingly large number of the oil fields developed in the last 10 years, the production has been from limestone and dolomite. Although known to have been productive in a few localities, these rocks had never been regarded favorably as reservoir rocks. Neither of them is very porous. As already noted, some dolomite may show a porosity of 12 to 14 per cent; but, as the pores are commonly unconnected, this pore space is of little value as a reservoir. Chalks have a porosity of 15 to 25 per cent, but their openings are too fine, as a rule, for them to make satisfactory reservoirs. Some production comes, however, from the Austin and Annona chalks in Texas.

Limestone and dolomite make excellent reservoirs where they are fissured or channeled (see Fig. 154 *E* and *F*). Due to the solubility of these rocks, openings in them may readily be widened by water action, developing excellent cavities in which oil may accumulate. As solvent work in rocks takes place only above the ground-water level, a limestone exposed to erosion for a time and then buried is apt to be channeled just

below the resulting unconformity. A recent study by Howard¹ showed that reservoirs of this type constitute probably 95 per cent of the known limestone reservoirs. Large gushers occur especially in channeled limestones.

Shale as a Reservoir Rock.—Shale is an impervious rock. Some shales are sandy, however, and these contain more pore space. Due to the extremely small size of the constituent grains of a shale, the pore spaces between them are capillary and subcapillary in size, and thus any liquid in them could not be removed. If, furthermore, divisional openings (cracks or fissures) were to develop, the low crushing strength of shale would permit it to flow and close the openings. A very hard shale, if not too deeply buried, might be fractured and retain the openings; and, if there were numerous sets of such divisional openings intersecting one another, the rock might act as a reservoir (see Fig. 155). A notable example of such an occurrence is the Florence field in Colorado.

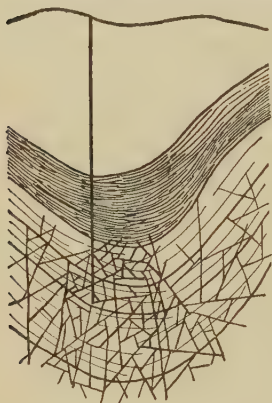


FIG. 155.—Ideal sketch of a fractured shale in a syncline, Florence field, Colo.

Effective Porosity.—The effective porosity of a reservoir rock is that part of the original pore space that will yield its oil. This is always less than the true porosity, for much of the oil clings to the rock grains. In a few wells, the production has indicated an unusually high effective porosity: 40 to 50 per cent or even higher.

Thickness of the Reservoir Rock.—The thickness of the reservoir rock is important in determining the total volume of oil that may be held in a reservoir. Not all of the reservoir necessarily holds oil; the upper part may be filled with gas and the lower part with water. The range in thickness of reservoir rocks is wide, as the following table shows:

TABLE 78.—RANGE IN THICKNESS OF RESERVOIR ROCKS IN DIFFERENT OIL FIELDS

Fields	Thickness, feet
Appalachian.....	5 to 35
Illinois.....	2 to 30
Mid-Continent.....	10 to 100
Louisiana.....	10 to 150
California.....	16 to 250

CAP ROCK

There must be impervious rocks above and below the reservoir rock to confine the oil and gas, although the one below may be absent if the

¹ HOWARD, W. V., A Classification of Limestone Reservoirs, *A. A. P. G. Bull.*, vol. XII, pp. 1153-1159, 1928.

lower part of the reservoir rock is thoroughly saturated with water. Any impervious rock can serve as a cap rock. Shale and clay are by far the most common ones, but dense limestone and dolomite are also satisfactory. Even cemented or very fine-grained sandstones have prevented further movement of oil along a bed. Dense shales, clays, and fine-grained limestones having the capillary and subcapillary openings filled with water are impervious to the passage even of gas, which can ordinarily move through much smaller openings than oil. A reservoir rock enclosed by any of these dense rocks would retain indefinitely any water, oil, or gas within it.

POSITION AND SHAPE OF THE RESERVOIR ROCK

The sedimentary rocks of the earth are seldom perfectly horizontal, although they often appear to be so. A dip of a few feet per mile cannot



FIG. 156.—Anticline in Madison limestone, Teton River, Mont. (*Photograph by W. A. Tarr.*)

be detected by the eye, but when mapped over a considerable area the departure from horizontality is readily noticeable. As a rule, a bed should have an inclined position to become a suitable reservoir, but the shape of the reservoir is also a factor.

Anticlines.—The ideal structure for the accumulation of oil is a fairly large anticline, particularly one having dips of less than 30° (Fig. 156). The dips may be greater, as in the Ventura Avenue (California) field, where they range from 30 to 60° on the sides of the anticlines (Figs. 157 and 158). The anticline was the first type of structure recognized as being influential in the accumulation of oil. The anticlinal theory (now widely known and generally accepted) was first

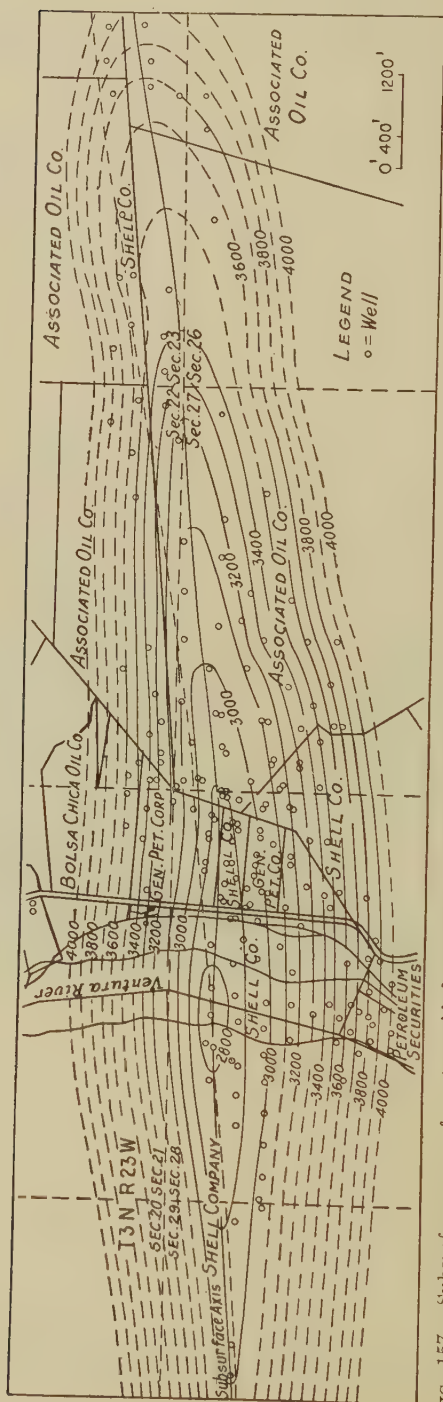


FIG. 157.—Subsurface map of a steep-sided anticline, Ventura Avenue Oil field, California. The map shows the structures at the base of the Gasnell shale, below sea level. Contour interval, 100 feet. See also Fig. 158. (After *Hentel*, A. A. P. G. *Bull.*, vol. XII, Fig. 5, p. 728, 1929.)

proposed by I. C. White in 1885. The careful mapping of thousands of oil pools since that time has shown that this type of structure predominates in them, but a large number of productive structures (determined by studying the subsurface geology from well logs) has been found that

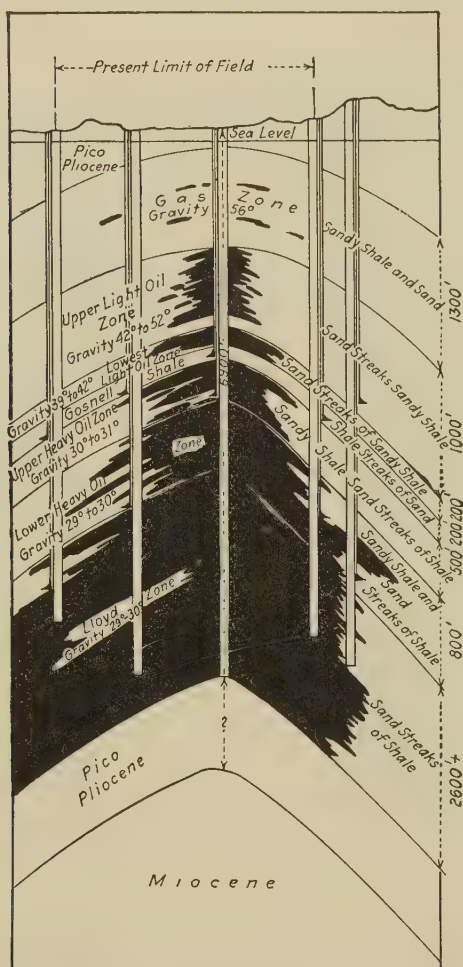


FIG. 158.—Cross section of the Ventura Avenue oil field of California, showing the steeply dipping sides of the anticline and the oil zones. Depths shown in feet. The dips on the flanks of the anticline range from 30 to 60°. (After Hertel, A. A. P. G. Bull., vol. XII, Fig. 6, p. 730, 1928.)

are modifications of the true anticline, and still others which are not anticlines.

A vast amount of study has been devoted to the form, size, and origin of these anticlinal structures, because of their fundamental bearing upon the occurrence of oil, and especially because they may furnish surface

evidence of oil below. It is far beyond the scope of this volume to attempt a complete discussion of these structures, and for additional information the student is referred to the numerous volumes on the geology of oil and gas. Only the essentials of the major types of structure will be given here. Figures 159, 160, 161, and 162 illustrate the more common types.

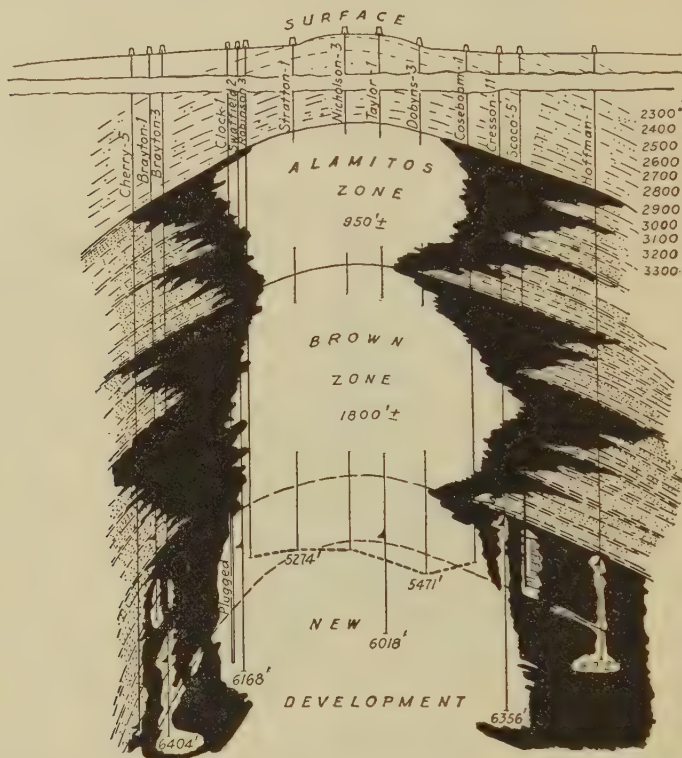


FIG. 159.—Ideal cross section through the Long Beach oil field of California. Depths shown in feet. Note the great vertical distribution of the oil. (After Jensen and Robertson, *A. A. P. G. Bull.*, vol. XII, Fig. 11, p. 644, 1928.)

Distribution of Oil, Gas, and Water in Anticlines.—In an ideal anticline (Fig. 162) containing the three commonly associated products, water, oil, and gas, the gas occurs at the top, the oil next below (probably well down the sides of the anticline), and the water lowest of all. This separation is due to differences in the specific gravity of the three substances and is usually very complete. If no gas is present, the oil will be at the crest of the structure, and if gas and oil (or oil alone) are present, the oil will move down the sides of the structure into the syncline (Fig. 155). Such occurrences are more common than many suppose.

Causes of Anticlines.—Simple folded anticlines are due to diastrophic forces, usually lateral compression. Some show uniform dips on each

side and at the ends, others are extremely asymmetrical. Variations in the dips on the sides have formed local points of accumulation for oil. Faulting frequently accompanies the folding. Some anticlinal structures are formed by the deposition of sediments on an old erosional surface bearing hills. Differential settling of the sediments has been suggested

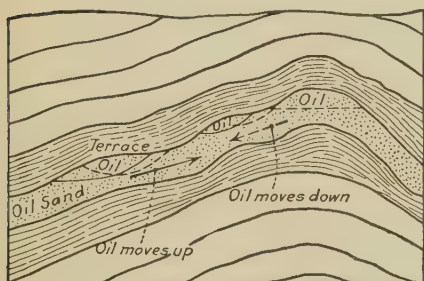


FIG. 160.—Anticline showing terraces and the position of the oil in the terraces when the oil moves up or down.

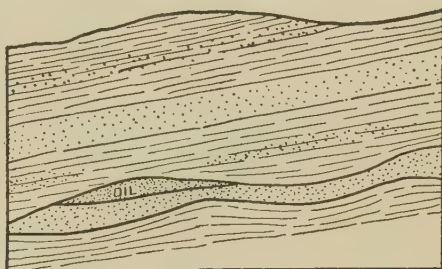


FIG. 161.—Oil occurring at the top of a sandstone (of irregular thickness) of which there is no surface evidence.

as a possible cause of anticlines. A series of interbedded lenticular beds would show some elements of anticlines.

Salt Domes.—Probably no more interesting type of structure has been found than the small domes containing cores of salt, which occur in the Gulf Coast region in Texas and Louisiana (see Fig. 163). These domes

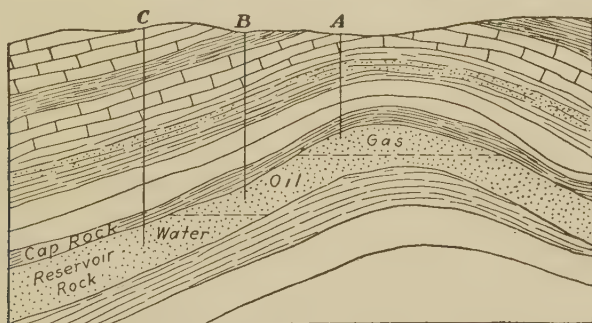


FIG. 162.—Ideal section of an anticline showing the cap and reservoir rocks and the position of the gas, oil, and water.

are rarely 2 miles in diameter, and the dips on their sides are steep. There is usually a cap rock of limestone or gypsum and anhydrite over the salt core. Sulfur occurs in the limestone and gypsum in some of the domes. The salt cores have nearly vertical sides. The thickness of the cores is unknown, as drills, having penetrated the salt to depths greater than 3,500 feet, have not reached the bottom. Oil and gas are found in these domes; and in some pools, the production has been very large (Fig. 164). Salt domes occur also in Germany, Rumania, and Mexico.

The origin of these unique salt columns has called forth a great deal of discussion during the last 25 years, both in America and in Europe. Many of the theories advanced have little evidence to support them. That held by Harris¹ is that salt solutions from below, rising toward the surface, deposited their salt load and the resulting crystallization forced the column of salt upward through the sediments. This hypothesis was widely accepted for a number of years, but recent studies have

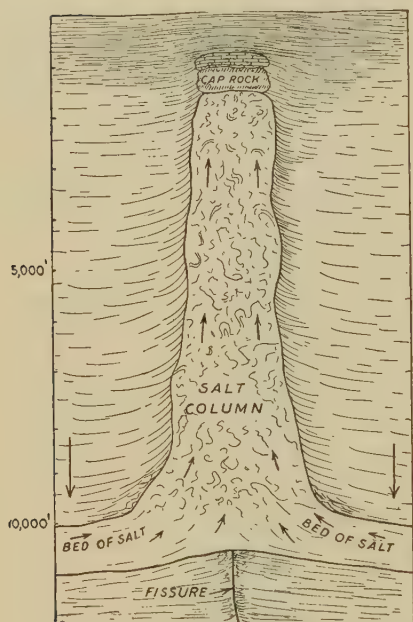


FIG. 163.—Hypothetical interpretation of the origin of a salt column forming a salt dome. Cap rocks consist of limestone and gypsum. Black dots in cap rock represent sulfur. Oil may occur in either rock. The pressure at 10,000 feet would be about 11,500 pounds per square inch. Curved lines in salt column indicate crumpling of salt as it flows upward.

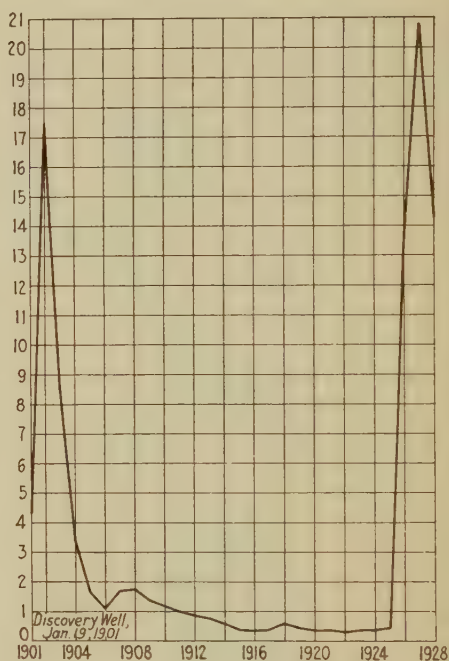


FIG. 164.—Curve showing the rapid increase in production in the Spindletop field, Texas; its rapid decline; long period of low production; the rediscovery of oil by deeper drilling; and the second rapid rise and decline. (Data from U. S. Mineral Resources.)

failed to give it support. The most widely accepted theory at present is that the salt was derived from deeply buried salt beds and has been forced toward the surface along weak places in the rocks by the lateral and vertical pressure. It is assumed to have moved by solid flowage, a view supported by the character of the salt and the flow lines in it (see Fig. 228, p. 628). The adequacy of vertical pressure alone to accomplish

¹ HARRIS, G. D., The Geological Occurrence of Rock Salt in Louisiana and Texas, *Econ. Geol.*, vol. IV, pp. 12-34, 1909.

the upward flow has been questioned by some, but there is no reason for excluding lateral pressure; and, as the writer of this book has long taught his students, movement is made possible by the highly perfect cubic cleavage of salt. This cleavage permits the salt mass to flow by gliding along perfect cleavage planes within the crystals. An analogous phenomenon is common in calcite, making possible the solid flowage of marble. The source of the cap rocks is still an open question.

Other Suitable Reservoirs.—Numerous non-anticlinal structures contain oil and gas. Some are due to the lenticular (or other) shape of the reservoir rock, and others are due to faulting or unconformities. Seepages of heavy asphaltic materials may seal up a bed. More rarely,



Fig. 165.—Lenses of sand in shale and limestone.

intrusive igneous rocks cut across sedimentary rocks, sealing them up so that they become reservoirs.

Lenticular Beds.—Lenticular beds of sand within shales or limestones furnish suitable reservoirs (Fig. 165). These beds occur, in some degree, in most fields but are especially common in the Mid-Continent field, where some have been wonderfully productive. If small, lenses must have derived most of their oil from the surrounding rocks; if large, considerable lateral migration must have taken place. A sand pinching out brings about a closure and may form a splendid pool if the volume of the sand is sufficient. A fine illustration of this type is the Glenn Pool in Oklahoma (Fig. 166).

Reservoirs Caused by Faulting.—Faulting may occur, and the displacement may be sufficient to bring an impervious bed opposite a porous one, which is thus sealed up and becomes a suitable structure for oil (Fig. 167). Certain California fields produce from sands that are sealed up in this manner. The fact that the wells are all close to the fault zone results in a linear arrangement of the wells in these fields.

The movement along a fault plane may develop a finely ground, impervious material that effectively prevents gas, oil, or water from

crossing the fault zone. The rocks on each side of the fault are thus sealed up (Figs. 168 and 169).

Reservoirs Caused by Unconformities.—Unconformities are often factors in the formation of oil pools. If the beds above the unconformity

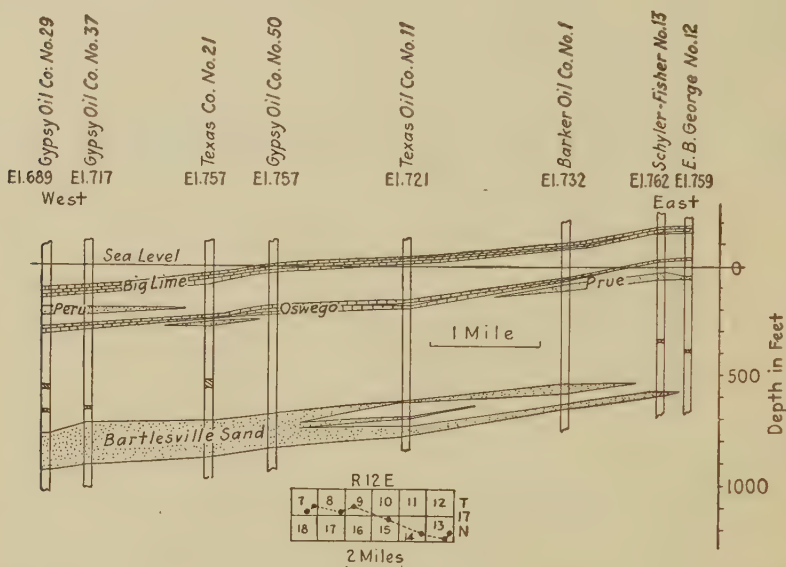


FIG. 166.—West to east cross section through Glenn pool, Oklahoma, showing pinching sands. (After Wilson, A. A. P. G. Bull., vol. XI, Fig. 4, p. 1,063, 1927.)

are impervious, they may seal up a porous member below. An accumulation of oil at the unconformity is then possible. This is especially true in the case of angular unconformities (Fig. 170), but it may also occur where the beds are essentially parallel. There is scarcely an oil field in



FIG. 167.—Reservoir formed as the result of faulting that placed an impervious bed opposite a porous bed.

which pools due to unconformities are not found. Oil associated with unconformities is common in the fields of central, northern, and western Texas and of California.

By means of an unconformity, an oil-bearing member may be brought into contact with a porous formation, which permits the transfer of oil and gas from an older

geologic formation to a younger, or *vice versa*. This type of migration is very common.

Reservoirs Caused by Igneous Intrusions.—Intrusive igneous rocks have been the means of sealing up reservoir rocks in a few localities,

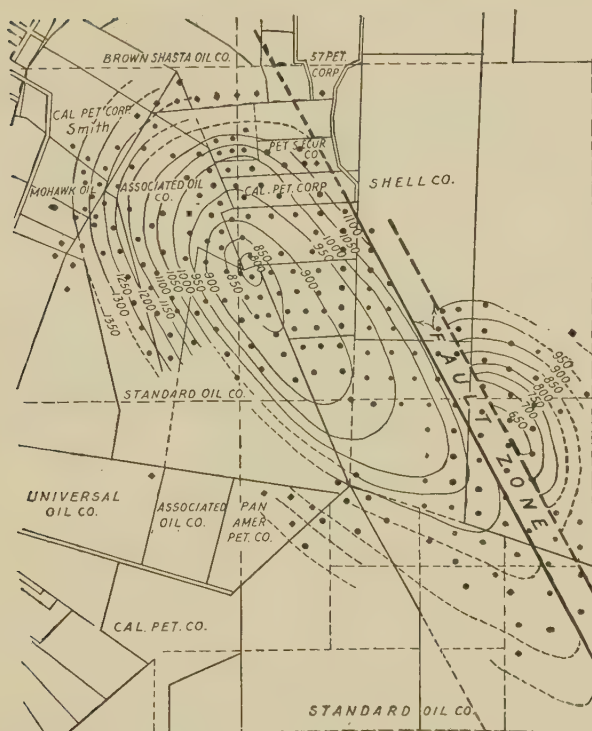


FIG. 168.—Subsurface contour map of the Inglewood oil field (Vickers zone), California. Contour interval, 50 feet. Contours show depth in feet below sea level to the top of the Vickers zone, which is the upper producing zone. Note the fault zone on the right. See Fig. 169, which shows the effect of this fault on the structure and occurrence of the oil. (After Jensen and Robertson, A. A. P. G. Bull., vol. XII, Fig. 6, p. 638, 1928.)

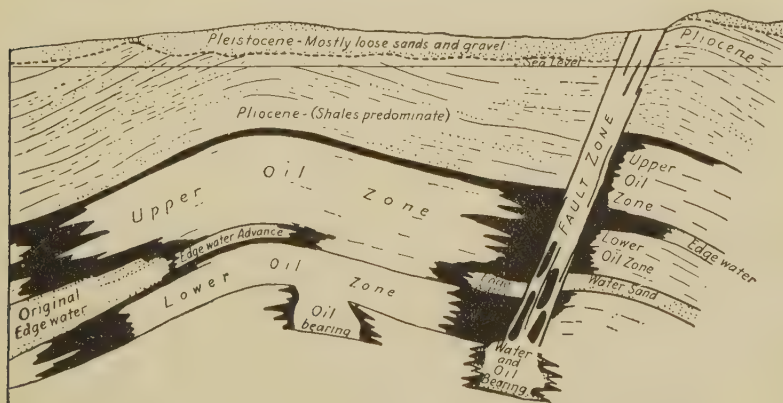


FIG. 169.—Ideal west-east section through the Inglewood oil field of California, showing relation of Pleistocene to Pliocene sediments and upper and lower oil zones with edge-water sands; also relation of fault to structure. Note the accumulation of the oil against the fault plane. (After Jensen and Robertson, A. A. P. G. Bull., vol. XII, Fig. 7, p. 639, 1928.)

notably in Mexico. The intrusive may be a dike but is usually a volcanic plug or neck, from which numerous sills spread out laterally. The oil, following the porous rock up the dip, was trapped under these sills or against the impervious igneous rock.

Reservoirs Caused by Seepage and Evaporation.—A less frequent means of sealing up a bed is by oil seepage and subsequent evaporation of the

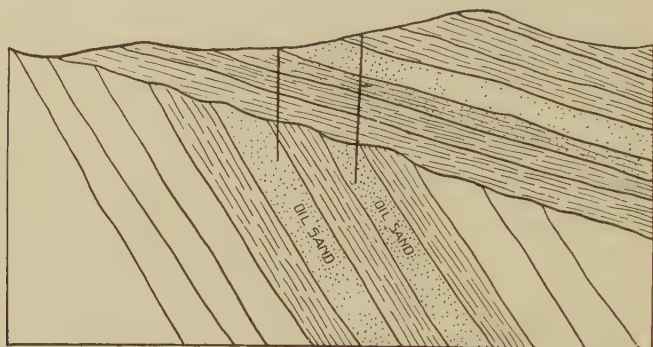


FIG. 170.—Oil in a reservoir sealed by an unconformity.

lighter oils. This leaves a solid or semisolid plug that aids in retaining the oil below (Fig. 171). Such deposits are called “brea” in California.

Surface Criteria for the Location of Oil Pools.—Aside from the commonly known and very essential surface evidence, *i.e.*, anticlinal structure, there are many other criteria for the occurrence of oil. Clapp has gathered them into a table, which follows:

TABLE 79.—FUNDAMENTAL SURFACE CRITERIA FOR OIL OCCURRENCE¹

1. Do “surface indications” exist?
2. Are the rocks of sedimentary origin?
3. Is the age of the strata (in part at least) similar to that prevailing in some known oil or gas field?
4. Does a possible source of origin exist? If this is not apparent, may it nevertheless be present?
5. Do porous beds or reservoirs exist in which oil may be held in commercial quantity?
6. If so, does sufficient “cover” exist above those beds to prevent oil or gas from escaping to the surface and from being lost?
7. Are the strata so slightly metamorphosed by heat or pressure that the oil has presumably not been driven away?
8. Does geologic “structure” exist suitable for concentrating oil or gas in commercial quantity?
9. Are the hydrostatic conditions such as may not prohibit the accumulation of oil in pools?

If an affirmative answer can be given to each of these questions for a given area, it would be safe to put down a test well.

¹ CLAPP, F. G., A. A. P. G. Bull., vol. XI, p. 683, 1927.

The amount of mapping of surface structures that has been done in recent years by geologists for oil companies and private individuals is enormous, and undoubtedly every portion of the United States, where the other necessary criteria are present, has been mapped. The finding of a structure, even where the other criteria are also apparently favorable, does not always mean production. For example, not 50 per cent of the structures drilled in Wyoming have been productive.

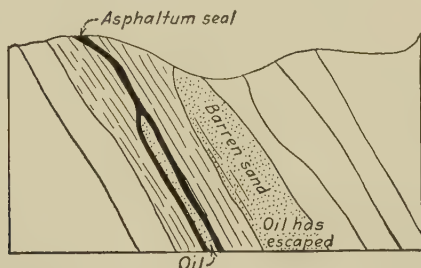


FIG. 171.—Sandstone sealed by asphaltum or brea formed from oil that escaped from the bed.

Subsurface Studies.—Many structures exist of which there are no surface evidences, and therefore methods of subsurface work have been devised. A great deal of important data has been secured by carefully working out the details of underground structure from well logs. More recently, these studies have been supplemented by petrographic studies of the formations encountered and by micropaleontologic studies. These subsurface studies have become indispensable in working out the details of sand lenses and of pools originating in connection with unconformities, both being indeterminable from the surface.

The surface and the subsurface contour maps of the top of the producing horizon in several adjacent pools in Marion and Butler counties, Kansas, are shown in Figs. 172 and 173. The close association of the production with the "highs" of the structure is readily seen in Fig. 173. A cross-section of this field is also given (Fig. 174), which illustrates how the position of the beds can be determined from the study of well logs. A carefully worked-out well log is given in Fig. 175. It is the log of the only well in the Burbank field to reach granite. The care exercised by all companies in keeping well logs is proving worthwhile in subsurface studies. How subsurface work brings out the effects of faulting is well shown in Figs. 168 and 169.

Geophysical Methods.—The impossibility of determining the kind of rocks or their position below the surface in areas where they are essentially flat or are buried under later deposits has led to the adaptation of various physical methods to the study of subsurface phenomena. The methods utilized are based upon density or gravity observations and

the rate of conductivity of vibrations or electrical impulses through the rocks. The two most widely used instruments are the torsion balance

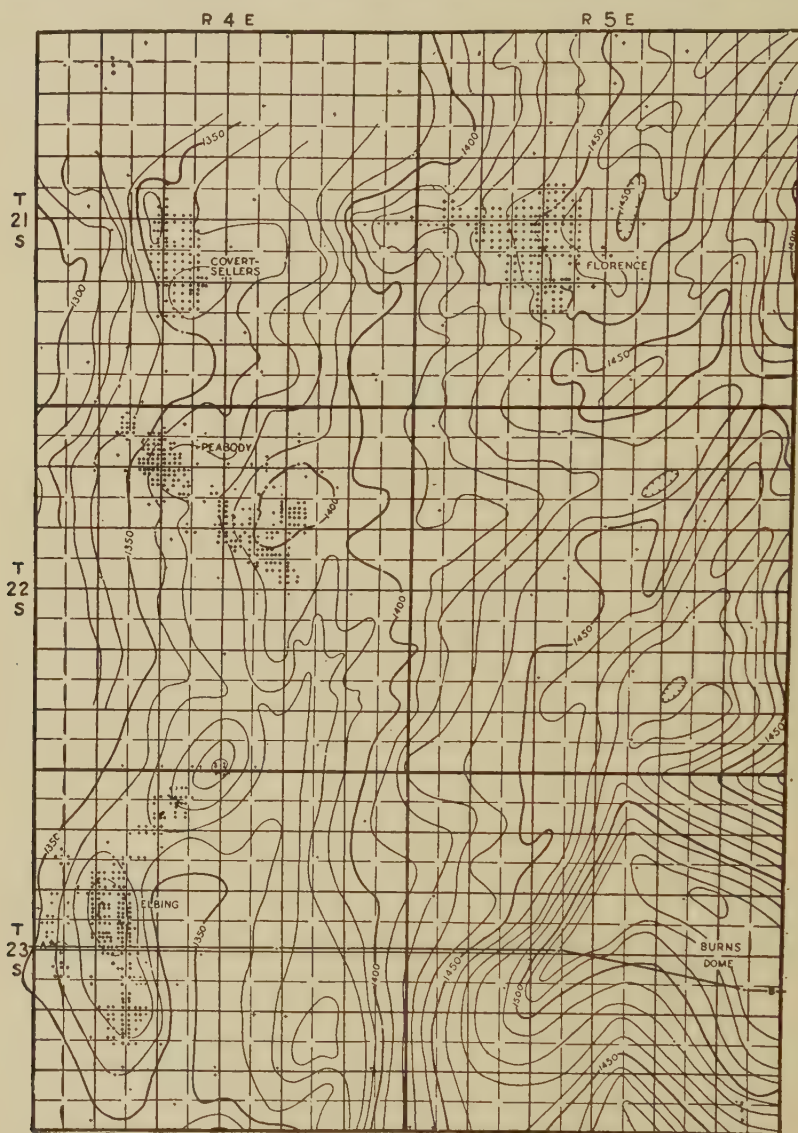


FIG. 172.—Surface structure in the Elbing, Peabody, Covert-Sellers, and Florence oil fields in Butler and Marion counties, Kan. Compare with the structure on the Ordovician about 2,500 feet below (see Fig. 173). See also the cross section in Figure 174. Contour interval, 10 feet. Scale, one township, approximately 6 miles square. (After Thomas, *A. A. P. G. Bull.*, vol. XI, Fig. 1, p. 921, 1927.)

and the seismograph; but others are the geophone, magnetometer, and petrolometer. Their most successful use, so far, has been in locating the

salt-dome structures of the Gulf Coast region. It is claimed that from 1924, when geophysical methods first came into use, to 1928, 64 domes (not all are salt domes; some are geophysical "highs") have been located by geophysical methods. Thirty of these were found in 1928. Drilling

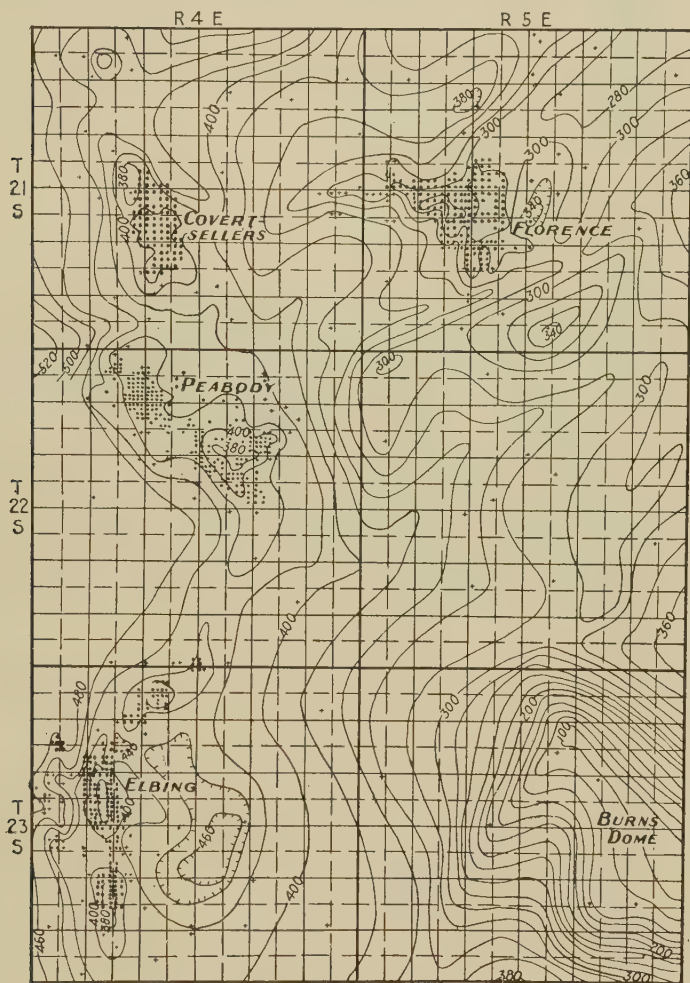


FIG. 173.—Subsurface structure on the Ordovician producing horizon in the same fields as shown in Fig. 172. Contour interval, 20 feet. Scale, one township, approximately 6 miles square. (After Thomas, A. A. P. G. Bull., vol. XI, Fig. 2, p. 923.)

of these highs has shown that the estimated depths to certain horizons have been satisfactorily accurate. An example is the Sugarland dome, Fort Bend County, Texas, worked out by the geophysical department of the Humble Oil and Gas Company. Their study indicated that the cap on the dome lay between 3,000 and 3,600 feet below the surface. Oil

was actually discovered at 3,506 feet. Salt domes, because of the difference between the gravity of the salt and the associated rocks, have proved especially satisfactory objects of study. If these methods can be improved to such a degree that actual variations in dip can be detected, they will be a great aid in cutting down the expense of wildcatting.

OTHER FEATURES OF ACCUMULATION OF OIL AND GAS

There are several other interesting features in connection with the accumulation of oil and its production that are worth noting. Among them are *the depth of oil and gas wells; the pressure in them and its cause; dry holes; crooked holes; water associated with oil; productivity and life of wells and fields.*

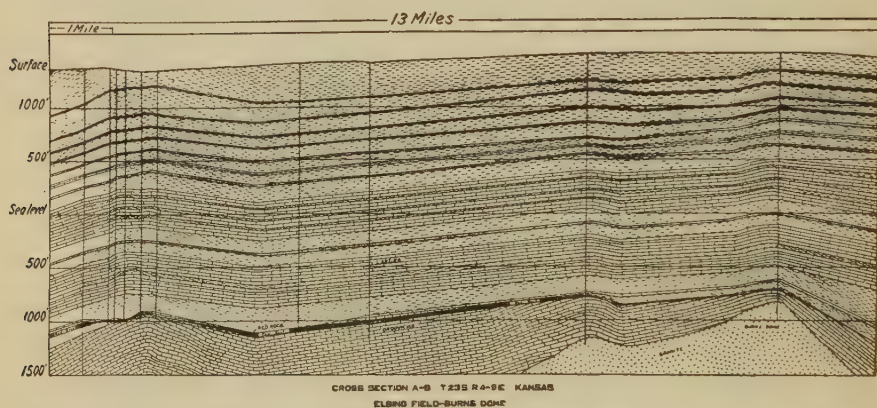


FIG. 174.—Cross section along A-B in Figure 172, through the Elbing field and Burns dome, Kansas. Compare with Figures 172 and 173. (After Thomas, A. A. P. G. Bull., vol. XI, Fig. 4, p. 927, 1927.)

Depth of Oil and Gas Wells.—Oil occurs from the surface (as seeps) to unknown depths. The depths differ widely, not only between two fields but also within a single field. There are shallow producing sands (a few hundred feet deep) and there are deep producing sands (1,000 feet or more) in the same field. Ten years ago, producing wells 4,000 feet deep were exceptional; today (1929), wells 6,000 feet deep are common. There are many over 7,000 and a few producers over 8,000 feet. Pennsylvania, West Virginia, Kansas, Oklahoma, Texas, Louisiana, New Mexico, and California all have wells over 6,000 feet in depth. There are no less than 58 wells over 7,000 feet deep in California (November, 1928), and at least 25 more will soon be completed. Three of them are over 8,000 feet. At present (December, 1928), the deepest producing well in the world is the Texan Oil and Land Company's in the Big Lake field in Reagan County, Texas. On Dec. 13, 1928, it was making 676 barrels of 53° gravity oil and 10,000,000 cubic feet of gas from a depth of 8,520 feet (1.62 miles).

Since wells at present reach depths of more than 8,000 feet, it is of interest to contrast the drilling of the early discovery period with that of the present. Drake began the first oil well early in 1859 and finally finished a 69-foot hole on Aug. 28, 1859. A drilling crew in 1928 drilled 1,000 feet of 11-inch hole in the Seminole field in Oklahoma in 40 hours. Still another crew drilled 1,104 feet in 24 hours. With good luck, a 6,000-foot hole can be drilled in the California fields in 3 months, though finishing jobs frequently add 2 or 3 months to the time. No doubt, a depth of 10,000 feet will be reached in certain fields at no distant date, and it is not improbable that oil and gas will be found in paying quantities at this depth. Beyond it, the physical conditions of temperature and pressure would become increasingly unfavorable to the occurrence of petroleum, to say nothing of the cost of drilling to such depths.

The temperature in some of these deep wells is as high as 77°C. (170°F.). The Ligonier well, No. 1842, at Ligonier Valley, Pennsylvania, is 7,756 feet deep and has a temperature of 10°C. at the top and 77°C. at the bottom. The Texan Oil Company's deep well in the Big Lake pool, Reagan County, Texas, had a temperature of 77°C. at 8,300 feet.

Pressure in Gas and Oil Wells and Its Cause.

Pressure.—The oil and gas, as found in the rocks, are usually under pressures which differ widely even in the same area and in parts of the same pool. The pressure in a well is erroneously called "rock" pressure. The overlying rocks have nothing to do with the pressure under which the oil, water, and gas exist in a reservoir. The openings in the reservoir rock were there before the oil and gas occupied them, and the rock itself was fully supporting those above it. The liquids in the reservoir merely occupied the interstices and in no way supported the weight of the overlying rocks. The term "pressure" is sufficient in referring to the pressure shown by the gas, oil, or water, although other names have been suggested for it.

Causes of the Pressure.—The pressure is attributed to (1) the expansive force of the confined gas, (2) the depth below the surface (usually brought to

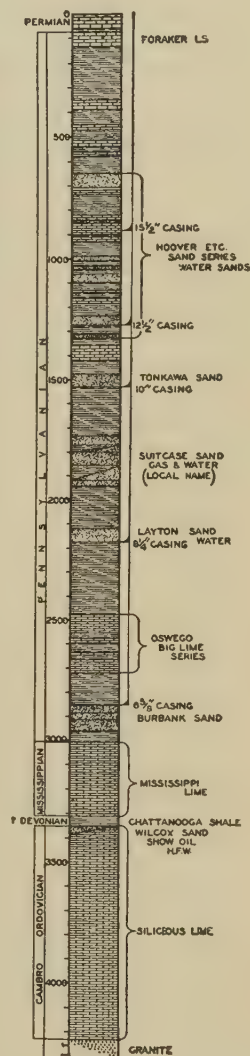


FIG. 175.—Type log, Burbank field, Osage and Kay counties, Okla. This is an excellent log and gives much information. (After Sands, A. A. P. G. Bull., vol. XI, p. 1053, Fig. 5, 1927.)

bear upon the oil and gas by the water and therefore called "hydrostatic pressure" or "head"), (3) *the lessening of the reservoir space due to the process of cementation going on in the rock*, and (4) *the addition of more gas or oil from the adjacent rocks*. The pressure in any one well is probably the result of some combination of these various factors, especially of the first two.

The depth below the surface, or the hydrostatic head, is probably the most fundamental factor, because the pressure in all oil fields varies with the depth, although not directly. A column of water 1 inch square and 1 foot high weighs 0.434 pound, or 43.4 pounds per 100 feet. If the water column is equivalent to the depth of the well, the hydrostatic pressure (*i.e.*, the weight of a column of water of a given height) would be 434 pounds per square inch for a well 1,000 feet deep. The pressure in the Richland gas field of Louisiana was 1,200 pounds per square inch and the hole was 2,440 feet deep, showing that the pressure in this well was essentially the same as the hydrostatic pressure. The producing horizon in Goose Creek dome in Texas is from 3,000 to 3,700 feet deep. The first wells drilled there showed a pressure of about 1,800 pounds. A big gas well, 2,827 feet deep, in De Soto Parish, Louisiana, showed a pressure of 1,230 pounds. A gas well (production from 45,000,000 to 50,000,000 cubic feet per day) at Rangely, Colorado, was 2,954 feet deep and had a pressure of 1,275 pounds. This was within 7 pounds of the ideal hydrostatic pressure. Data of this kind could be given for oil and gas fields in all parts of the United States; which shows that hydrostatic pressure is undoubtedly one of the most important causes of pressure in oil and gas wells, if, indeed, it is not the most important one.

The pressures that are due to the hydrostatic head are largely confined to wells less than 4,000 feet deep, which is evidence that meteoric waters do not penetrate to great depths from the surface. Some interesting data that further support this statement came to hand after the above was written. Mills,¹ in discussing the depth-pressure relationship in gas wells of Oklahoma, gives some valuable tables of depths and pressures. In a group of eight wells whose average depth was 2,309 feet, the average initial gage pressure, per 100 feet of depth, was 42.16 pounds, or within 1.24 pounds of the theoretical pressure of 43.4 pounds. Wells having depths over 4,000 feet (the average was 5,272 feet) showed, on the other hand, an average gage pressure of only 33.49 pounds per 100 feet, or nearly 10 pounds less than the theoretical pressure. In these wells, it is evident that the pressure is not due to a head of water equal to the depth of the wells. As before stated, the pressure may not be equal to the hydrostatic head even in wells less than 4,000 feet deep. Another table by Mills giving depths and gage pressures in wells of Osage County, Oklahoma,

¹ MILLS, R. VAN A., Gas Pressure and the Recovery of Crude Oil, *Oil and Gas Jour.*, vol. XXVII, No. 31, pp. 28, 95, 1928.

showed an average pressure of 36.8 pounds per 100 feet of depth. A careful study of the structural form of the sands in Osage County would doubtless reveal why the pressure was less in this area. The very deep wells (those from 4,000 to 8,000 feet) thus show pressures less than the hydrostatic head. The pressures in some of the 8,000-foot wells at Long Beach, California, were not much over 12.5 pounds per 100 feet and were evidently due to a combination of causes rather than to hydrostatic head.

Some wells, however, produce from lenses that are completely sealed off from any possible water connection with the surface. In such wells, *the expansive force of the gas* is probably the important cause of pressure. If no gas is present, the pressure would be due to *loss of space caused by cementation* and to the constant *influx* (due to capillarity) *of more oil into the reservoir* from the surrounding rocks. Heat has been suggested as a factor, but it seems to be inconsequential.

That the gas associated with oil is a factor in the pressure is shown by the decrease in production as the gas pressure falls. This is a common experience in all oil fields in the United States where the oil and gas are associated. In fields where gas occurs alone, the pressure declines rapidly if the gas is wasted or drawn off excessively. Bauer¹ has pointed out that the pressure declined 75 per cent (from 420 to 100 pounds) in 15 months in the wonderful Borger gas field in the Texas Panhandle. As much as 325,000,000 cubic feet of gas was wasted daily in this field.

Although a considerable number of gas wells show pressures of 1,000 pounds, the majority average 500 pounds or less. Oil wells rarely show the high pressures found in gas wells, but undoubtedly some of the great gushers had high pressures. The high gas pressures in some wells cause considerable difficulty during drilling, and it is frequently necessary to introduce into the well a mud composed of finely ground hematite or barite (each having a high specific gravity) as an aid in holding back the gas.

Dry Wells.—From 1917 to 1927, an average of 26,080 wells was drilled annually in the United States, of which about 24.1 per cent was dry (Fig. 176). There has been a steady increase in the percentage of dry holes since 1910. Of the wells drilled in 1910, 16 per cent was dry. During the first half of 1928,² 33.79 per cent was dry, and only 55.03 per cent produced oil. This high ratio of dry holes is evidence that in spite of a widespread use of our knowledge of structural, paleontological, and geophysical factors, the wildcatter has gone beyond the favorable areas and has taken more and more remote chances.

The percentage of dry holes in the different states varies widely. In 1926, it was as high as 42.7 per cent in Colorado. The average initial

¹ BAUER, C. MAX, Gas a Big Factor in the Texas Panhandle, A. A. P. G. Bull., vol. XII, p. 165, 1928.

² According to figures collected by the *Oil and Gas Jour.*

daily production per well, however, was 358 barrels for the successful wells, a production exceeded only by that of California, where 429 barrels per well was recovered. Of the holes drilled in California that year, 24 per cent was dry. Pennsylvania and New York had the lowest percentage (only 5.5 per cent); but the initial daily production per well was also low, averaging 4 barrels. More than 2,000 wells were drilled in Kansas, Oklahoma, and Texas in 1926, and the average percentage of dry holes for each state, respectively, was 33.5, 32.4 and 33 per cent. The following table is of interest because it shows that, although the average number of dry holes had increased over previous years, the average initial daily production for the productive wells had also increased. In 1928,

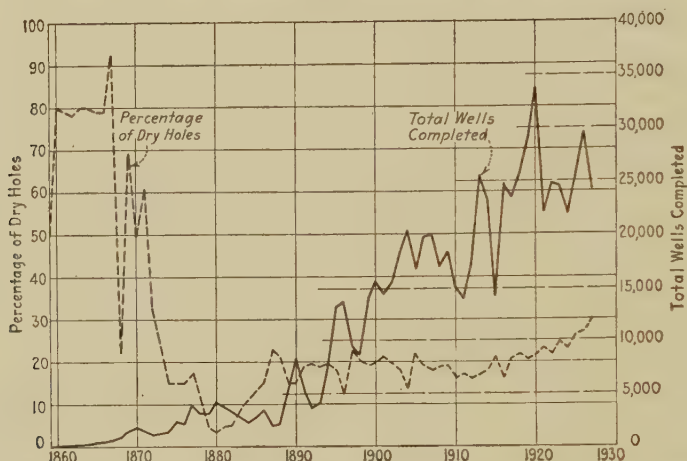


FIG. 176.—Total wells completed and the percentage of dry holes in the United States from 1859 to 1927. (Data U. S. Geol. Survey Bull. 384, pp. 40–41, 1909, and U. S. Mineral Resources, 1927, Part 2, p. 577.)

there were 7,000 fewer wells drilled than in 1926, but there was nearly double the initial daily production, the average for 12,526 wells being 667.9 barrels per well. This very high average was due to the exceptionally productive holes drilled in Texas, Arkansas, and California.

TABLE 80.—COMPARISON OF WELLS COMPLETED IN THE UNITED STATES DURING 1928 AND 1926¹

Jan. 1 to Dec. 31	1928	Percent- age	1926	Percent- age
Wells completed.....	22,331	....	29,319	....
Total initial daily production, barrels....	8,365,778	....	3,683,787	....
Number of dry holes.....	7,078	31.7	7,965	27.0
Number of gas wells.....	2,727	12.2	2,341	8.2
Number of oil wells.....	12,526	56.1	19,013	64.8
Average initial daily production, barrels .	667.9	....	194	....

¹ Oil and Gas Jour., Jan. 31, 1929, p. 111.

Crooked Holes.—Since 1895, over 750,000 wells have been drilled for oil and gas in the United States. During the first 60 years, these holes were relatively shallow, and little attention was paid to their course underground. The supposition was, of course, that they were vertical holes. It has recently been discovered, however, that crooked holes¹ are far more common than was suspected. They are especially apt to occur when rotary tools are used in drilling. The departure from a

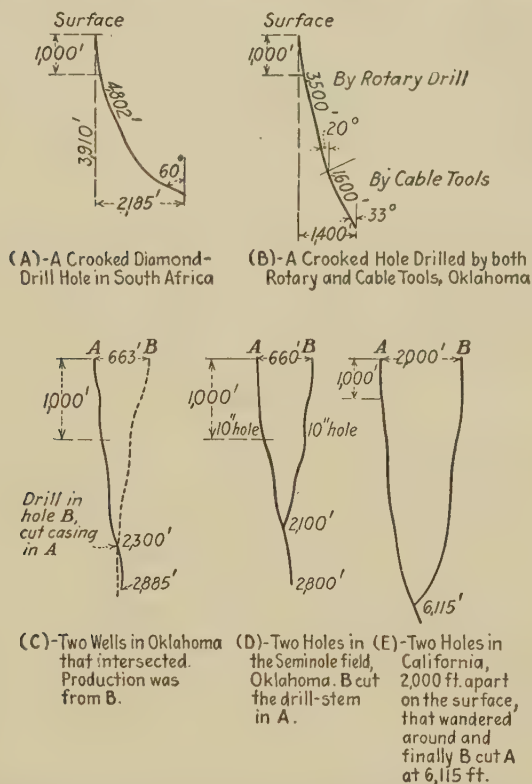


FIG. 177.—Ideal sketches of crooked holes. (Data for B and D from Dwyer, *Oil and Gas Jour.*, Aug. 23, 1928, p. 29; A, from Goodrich, *idem*, Nov. 15, 1928; C, from Mills, *idem*, Aug. 23, 1928, p. 30; and E, from Lahee, *A. A. P. G. Bull.*, vol. XIII, p. 1, 119, 1929.)

vertical hole in a few extreme cases as much as 30 to 40° and in one diamond-drill hole in South Africa it was actually 60°. In another similar type of hole in South Africa, the departure from the vertical was 3,632 feet in a hole 6,625 feet deep. Figure 177 shows graphically a few interesting examples of crooked holes. Several devices for surveying the course of drill holes have recently been perfected, by means of which surveys have been made that have revealed astonishing deviations from

¹ LAHEE, F. H., Problem of Crooked Holes, *A.A.P.G. Bull.*, vol. XIII, p. 1095, 1929.

the vertical. A 6,300-foot well in California was found to have roamed about under 9 acres of ground. The survey of another hole, 4,411 feet deep, showed that it was actually off the structure. Crooked holes present an engineering problem that will require careful study to solve, though frequent measurements for inclination during drilling are already obviating much of the difficulty.

The Water Associated with Oil.—Water is usually found associated with oil, but in some sands it is absent. The water is normally salt water, but in a few sands, it is believed to be artesian or meteoric. The salt waters were buried with the rocks in which they are found and so represent ocean water that has undergone some change. Their resemblance to ocean water is evident by comparing analysis A with analyses B and C in the following table:

TABLE 81.—ANALYSES OF VARIOUS TYPES OF WATER

(A = ocean water, B = brine or connate water, C = brine or connate water, D = surface carbonate water)

	A	B	C	D
	Percent- age	Percent- age	Grams per liter	Percent- age
Chlorine, Cl.....	55.292	61.38	84.35	1.7
Bromine, Br (and I).....	0.188	0.26	.....	.....
Sulfate, SO ₄	7.692	0.02	.....	6.3
Carbonate, CO ₃	0.207	.....	.....	.....
Sodium, Na.....	30.593	24.50	37.67	2.9
Potassium, K.....	1.106	1.97	.....	.....
Calcium, Ca.....	1.197	9.56	11.94	15.9
Magnesium, Mg.....	3.725	0.94	1.81	4.6
Bicarbonate, HCO ₃.....	.....	.....	0.04	68.6
Fe''.....	.....	0.06	0.03	.....
SiO ₂.....	.....	.....	0.21	.....
Sr.....	.....	1.31	.....	.....
	100.00	100.00	136.05	100.00

A. Mean of 77 analyses of ocean water from many localities, collected by the *Challenger* expedition. W. Dittmar, analyst. Salinity 3.301 to 3.737 per cent. (F. W. Clarke, *Data of Geochemistry*, U. S. Geol. Survey *Bull.* 770, p. 126.)

B. Analysis of brine from sandstone of early Devonian age; depth 6,260 ± to 6,300 feet. From gas well 8 miles southwest of Imperial, Washington County, Pennsylvania. Specific gravity of water 1.211; 263.64 grams of dissolved solids per kilogram. George Steiger, analyst. (Mills and Wells, U. S. Geol. Survey *Bull.* 693, p. 30.)

C. Brine from Big Injun sand; depth 1,425 feet; Carter Oil Company's well, No. 7, on Russell heirs' farm, near Paden City, Wetzel County, West Virginia. Production of water 5 barrels daily. S. C. Dinsmore, analyst. (Frank Reeves, *Econ. Geol.*, vol. XII, p. 374, 1917; Mills and Wells, *idem*, p. 37.)

D. Water from a well, 57 feet deep, on Brown's farm, Venice, Washington County, Pennsylvania. Analyses furnished by Kennicott Water Softening Company. (Mills and Wells, *idem*, p. 42.)

The principal changes in these waters are the loss of the sulfate (possibly due to sulfate-reducing bacteria) and magnesium and the increase of calcium. Some of these brines are important sources of calcium chloride and bromine. Analysis D is given in order to compare a dominantly carbonate water (most surface, well, spring, and many artesian waters are carbonate waters) with the connate type. Fresh waters may be buried in a series of sediments, just as is ocean water, but it is difficult to prove that this has occurred.

Salt water in a sandstone does not mean that oil will be found, for there are many sands containing brines from which no oil or gas has ever been produced. The encroachment of the water associated with oil constitutes a problem of much magnitude in oil recovery. The wells in the Hendricks pool in Winkler County, Texas, were averaging 42 per cent of water in July, 1928, and a few were flowing 90 to 95 per cent water. The encroachment of the water (known as "edgewater") in a pool is shown in Fig. 178.

Productivity of Wells and Fields.

The Rise and Decline in Productivity of Wells and Fields.—The daily production of wells during the early history

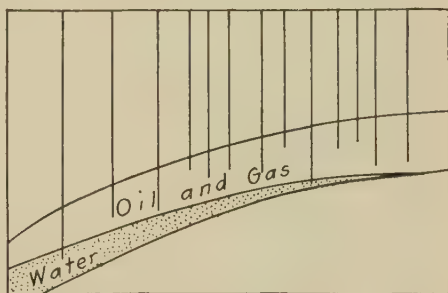


FIG. 178.—Edgewater wedging in under oil and gas in a reservoir as the oil and gas are removed. (After Beal, U. S. Geol. Survey Bull. 658, p. 49.)

of an oil pool is comparatively high but shows a rapid decline after the first year or two. Wells of the salt domes of Texas and Louisiana are especially subject to high initial daily production followed by a rapid decline. The Spindletop field, just south of Beaumont, Texas, is an excellent illustration of such production. The first well (the Lucas) reached the producing horizon (a very porous limestone) at 1,139 feet and had an initial production of 75,000 barrels. This was one of the largest wells in the United States. Most of the wells of this field ceased to flow within a few weeks or, at most, a few months. The production of the field rose rapidly to 3,600,000 barrels by the end of 1901 and to 17,420,000 barrels by the end of 1902 (see Fig. 164, p. 414); then it dropped almost as rapidly and for 20 years was very low. Deep drilling in 1926 revealed an even more productive horizon at 5,000 feet (from an area limited to 40 acres), and the production jumped to 13,441,000 barrels, or nearly 37,000 barrels daily. This was further increased in 1927. Sour Lake field, not far from the Spindletop pool in Texas, shows a somewhat similar history. The Seminole field in Oklahoma; numerous pools in western Texas; and Long Beach, Santa Fe Springs, and other pools in California show similar rapid initial rates of production and will show a

decline, though at a much slower rate because of the steps that are being taken to control the rate of production.

Average Initial Production of Fields.—The average initial production for individual wells may be high, but that for fields is generally low. In

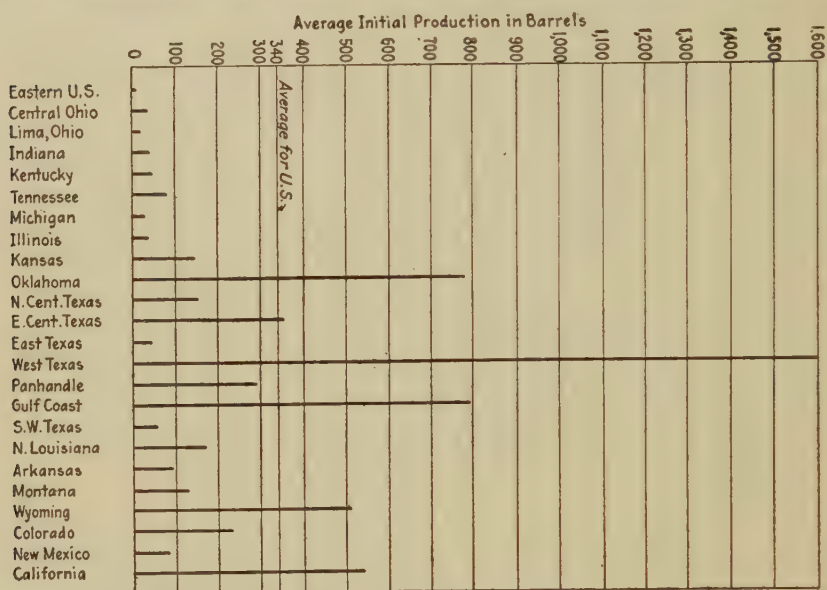


FIG. 179.—Diagram showing average initial oil production, by fields, for the United States in 1927. (Data from *Oil and Gas Jour.*, vol. XXVI, no. 38, p. 102, 1928.)

some fields, it is very low, indicating that most of the wells probably had to be pumped from the start. In 1927, 14,442 wells were completed in the

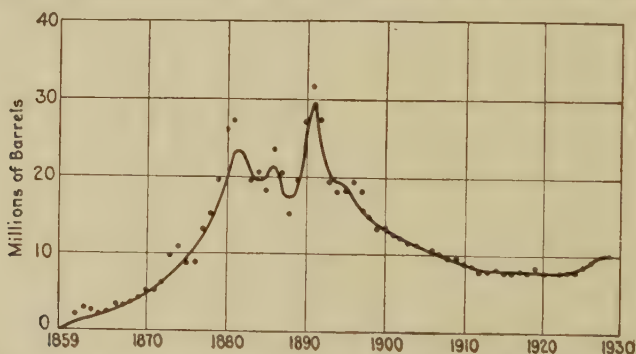


FIG. 180.—Curve showing the almost stationary character of the oil production in a field after its period of maximum production. The curve represents the production in Pennsylvania and New York up to 1881 and thereafter in Pennsylvania alone. (Data from *U. S. Mineral Resources*.)

United States. These had an average initial production of 340 barrels per well; but, as can be seen from Fig. 179, the variation in the different

fields is wide, ranging from 6.5 barrels in the eastern fields to 1,590 barrels in the newly discovered West Texas area. The average of initial production has been increasing over a period of years but shows considerable variation. As the production gradually declines, it becomes nearly stationary, as the curve for production in Pennsylvania shows (Fig. 180). Although new wells are drilled in these areas of declining production, they serve mainly to keep up the average, because the wells brought in during the late history of a field are relatively small producers. As a rule, a considerable number of these later holes are dry. The Bradford field in Pennsylvania has proved to be a notable exception to this rule, however. In 1928, there were completed in this field (which was 53 years old) 1,572 wells of which only 1 was dry and 11 were gassers. The average initial production of these new wells was between 2 and 3 barrels daily. Over the state line in Alleghany County, New York, 474 wells were completed with only 4 dry holes and 6 gas wells. The life of a field is thus seen to be extremely variable.

Exceptionally Productive Wells.—Some wells have produced enormous amounts of gas or oil. A gas well in the Corpus Christi district in San Patricio County, Texas, was brought in Dec. 31, 1915, with an initial capacity of 100,000,000 cubic feet of gas a day. It broke loose 2 weeks later and a week after that caught on fire and burned for 2 months before it was choked up. Since 1915, wells producing 100,000,000 cubic feet or more daily have been drilled in the Panhandle of Texas, in Louisiana, and in other places in the Mid-Continent field. Wells that produce more than 50,000,000 cubic feet of gas per day are common.

The amount of oil produced in 24 hours by some wells is enormous. One gusher (the famous "No. 4" of the Huasteca Petroleum Company) in Mexico¹ produced nearly 300,000 barrels a day. This well was in the Cerro Azul (Blue Mountain) pool northwest of Tuxpam, Mexico. The oil rose in a solid column, 598 feet high, before breaking, and continued the display for 8 days. It had a temperature of 50°C. (122°F.) and a



FIG. 181.—The discovery well in the Oklahoma City field, Okla., Dec. 4, 1928. This well was 6,402 feet deep when the gusher blew in. It averaged about 5,500 barrels daily during the first two weeks. A year later the well would not flow. (Photograph *Oklahoman-Times*.)

¹ WHITE, I. C., quoted in *U. S. Mineral Resources*, 1916, Part 2, p. 860.

gravity of 21.5° A.P.I. The well showed a pressure of 1,035 pounds when it was finally shut in. Measurements made as the oil overflowed the temporary reservoirs erected to hold it showed that the flow increased from 150,000 barrels on the fourth day to a daily 300,000 barrels when it was finally closed. One of the largest wells in the United States was brought in during August, 1928, in the Yates Pool, Pecos County, Texas. A short test on the well, which was 1,280 feet deep, indicated a potential production of about 125,000 barrels per day. Figure 181 illustrates a gusher in a well of relatively small production (about 5,500 barrels daily). Wells producing from 50,000 to nearly 100,000 barrels daily have been discovered in other parts of Mexico; in Persia; and in the United States (Texas, especially western Texas, and Louisiana).

Wells of Small Production.—Although wells having enormous productions are occasionally found, the production of the majority is small. On Dec. 31, 1927,¹ there were approximately 323,300 producing oil wells in the United States the average daily production of which was 7.7 barrels per well. In the majority of these wells, the pressure is so low that pumping is resorted to from the beginning. The production ranges widely in different fields, as the following table shows:

TABLE 82.—PRODUCING OIL WELLS AND THEIR AVERAGE PRODUCTION IN THE UNITED STATES, DEC. 31, 1927¹

State	Approximate number of wells	Average production per well per day, barrels
Arkansas.....	4,550	24.2
California.....	11,280	59.9
Colorado.....	170	51.7
Illinois.....	16,240	1.2
Indiana.....	2,060	1.1
Kansas.....	19,600	5.8
Kentucky.....	13,500	1.4
Louisiana.....	4,250	14.8
Michigan.....	300	6.2
Montana.....	980	15.3
New Mexico.....	250	14.0
New York.....	16,740	0.4
Ohio.....	37,600	0.5
Oklahoma.....	61,750	12.3
Pennsylvania.....	78,480	0.3
Texas.....	32,000	19.5
West Virginia.....	19,900	0.8
Wyoming.....	3,560	16.8
United States.....	323,300	7.7

¹ U. S. Mineral Resources, 1927, Part 2, p. 577.

¹ U. S. Mineral Resources, 1927, Part 2, p. 577.

Life of Individual Wells.—A question often asked is: how long is the life of an oil well? The answer would be as variable as is the production. Some wells have ceased to produce oil within a few weeks, and others have produced for years. The average age of wells in Texas has been estimated at 3 or 4 years and in Oklahoma and California at 8 to 10 years. There are wells in Pennsylvania, New York, and West Virginia that have produced continuously for 35 to 50 years. The relative life of wells depends on how rapidly production is made from them, other things being equal, of course. Some wells in New York and Pennsylvania are pumped at intervals of a week or 2 weeks and average from 1 to 5 gallons of oil per day. No less than 96,940 wells in Pennsylvania, Ohio, and Indiana averaged only 0.3 barrel of oil a day in 1927, and 153,680 wells in these states, New York, and West Virginia averaged less than 0.8 barrel per day. In 1928, 46.6 per cent of all producing oil wells in the United States yielded less than 1 barrel per day. The life of such wells must be very long.

Modern methods of improving the recovery from wells by flooding with water or repressuring with air or gas are increasing the life, and thereby the total production, of wells. In the Bradford field in Pennsylvania, the wells were flooded with water and the recovery was thus increased from 10 or 15 to 25 or 30 per cent of the original oil present. Other estimates place the recovery as high as 60 per cent.

Production per Acre and Spacing of Wells.—The amount of oil produced per acre is chiefly of interest because it has a bearing upon the questions of porosity, saturation, and recovery. Once a hole is drilled into a sand, it is essential that a maximum production be secured, for the total production of some wells has scarcely paid for their drilling.

The spacing of wells in a pool is a matter of importance in connection with the production per well. The usual practice is to drill one well to 10 acres (660 feet apart). Where the subdivision of the surface land is in small parcels, as town lots or 1-acre plots, wells are much more closely spaced. This is true at Santa Fe Springs and, to a lesser extent, at Long Beach, California. The rapid decline of the wells in the Spindletop field, shortly after its discovery, was partly due to the close spacing of the wells: about one per acre.

Table 83 gives not only the production per acre but also the total production and acreage of the leading fields in the United States from their discovery to the present time.

It is of interest to contrast two such fields as the Bradford field in Pennsylvania and the Spindletop in Texas; the one with its long life (53 years), its great production from a large area, and its low yield of 3,077 barrels per acre; the other, short-lived, only 390 acres in area, and having the tremendous production of 214,362 barrels per acre. The field at Long Beach, California, furnishes another interesting example of an enormous yield per acre.

TABLE 83.—PRODUCTION RECORD OF THE LEADING OIL FIELDS IN THE UNITED STATES TO JAN. 1, 1928¹

Year	Field and state	Total production, barrels	Producing acreage	Recovery per acre, barrels
1901	Midway-Sunset, California.....	616,948,073	35,364	24,323
1896	Coalinga, California.....	304,578,674	11,200	27,194
1912	Cushing, Oklahoma.....	283,894,274	21,850	12,993
1900	Kern River, California.....	265,941,977	6,521	40,772
1875	Bradford, Pennsylvania.....	261,182,000	85,000	3,072
1921	Long Beach, California.....	260,110,233	1,360	191,257
1922	Smackover, Arkansas.....	245,733,779	21,560	11,397
1916	Butler County, Kansas.....	207,679,731	23,750	8,744
1889	Salt Creek, Wyoming.....	191,529,122	20,480	9,352
1906	Glenn Pool-Kiefer, Oklahoma.....	187,018,535	18,590	10,060
1920	Santa Fe Springs, California.....	169,028,907	1,338	126,329
1920	Burbank, Oklahoma.....	149,008,605	20,150	7,395
1913	Healdton, Oklahoma.....	148,490,999	7,340	20,235
1926	Seminole area, Oklahoma.....	146,362,842	10,470	13,979
1920	Huntington Beach, California.....	126,964,839	1,752	72,470
1919	Burkburnett, Texas.....	125,704,548	18,080	6,952
1897	Fullerton, California.....	122,318,601	1,254	97,542
1902	Santa Maria, California.....	121,518,200	5,247 ²	23,159
1906	Caddo, Louisiana.....	119,786,380	32,200	3,720
1912	Coyote, California.....	117,115,462	2,100	55,769
1905	Humble, Texas.....	99,738,179	1,356	73,553
1922	Tonkawa, Oklahoma.....	96,692,111	3,420	28,272
1921	Mexia, Texas.....	84,038,338	3,704	22,689
1923	Powell, Texas.....	97,313,149	2,612	37,256
1901	Spindletop, Texas.....	83,601,501	390	214,362
1920	West Texas, Texas.....	82,423,667	11,880	6,938
1904	Sour Lake, Texas.....	71,124,077	3,645	19,512

¹ McIntyre, *Oil and Gas Jour.*, vol. XXVI, No. 37, p. 29, 1928.² Includes Casmalia, Cat Cañon, Lompoc, Santa Maria.

Factors Influencing Production per Acre.—The total production per acre depends upon the thickness of the sand, its porosity, the water pressure, the gas pressure, the viscosity of the oil, the rate of its withdrawal, and numerous other factors. It is of interest briefly to examine some of them.

Washburne¹ has computed that 1 acre of sand 1 foot thick will contain 7,758 barrels of sand. If the porosity of the sand is known, the number of possible barrels of oil to each foot of a bed can be estimated. The following table shows the possible quantity of oil present in sands of different porosities:

¹ WASHBURNE, C. W., The Estimation of Oil Reserves, *Am. Inst. Min. and Met. Eng.*, vol. LI, p. 646, 1916.

TABLE 84.—POSSIBLE AMOUNT OF OIL PER ACRE-FOOT OF SAND¹

Percentage porosity of sand	Barrels	
	Per 100 per cent saturation	Per 75 per cent saturation
5	387	290
10	775	581
15	1,163	872
20	1,552	1,164
25	1,939	1,454

¹ WASHBURN, C. W., The Estimation of Oil Reserves, *Am. Inst. Min. and Met. Eng.*, vol. LI, p. 646, 1926.

GEOLOGIC DISTRIBUTION OF OIL AND GAS IN THE UNITED STATES

The oil and natural gas in the United States come from Paleozoic, Mesozoic, and Cenozoic formations. The Ordovician contains the oldest oil horizons (an insignificant amount of gas has been reported from the Cambrian in New York); and the formations of each succeeding period produce some oil or gas, although that in the beds of some periods did not originate within the formation itself.

The oil production in the United States is greater from the Paleozoic than from either of the other two producing formations; the Tertiary is second; and the Mesozoic, third. The major part of the production of the world, however, comes from the Tertiary; the Paleozoic next; and, last, the Mesozoic.

The physical conditions during all the geologic periods were not adapted to an abundant growth of organisms or to the preservation of their carbonaceous remains; hence, little oil or gas occurs in some of them. There is good evidence to support the view that the oil in the Ordovician formation (especially that in the Mid-Continent field and possibly in the eastern fields) migrated into it from younger formations. There seems to be little doubt that the same is true of the Permian and Triassic and, probably, the Silurian. Some men think that part of the oil from the Lower Mississippian came upward from the Chattanooga shales. Furthermore, it is not unlikely that the oil from the Tertiary in the salt domes of the Gulf Coast migrated upward from the deeper Cretaceous formations. If the oil in these formations did come from other beds associated with them, the periods during which oil was formed abundantly are reduced to the Devonian, Mississippian, and Pennsylvanian of the Paleozoic; to the Comanchian and Cretaceous of the Mesozoic; and to the Tertiary (dominantly Miocene) of the Cenozoic.

TABLE 85.—THE PRODUCTIVE OIL AND GAS HORIZONS IN EACH STATE

State	Paleozoic						Mesozoic				Cenozoic Tertiary			
	Cam- brian	Ordo- vician	Silu- rian	Devo- nian	Missis- sippian	Pennsyl- vanian	Per- mian	Trias- sic	Juras- sic	Coman- chean	Creta- ceous	Eo- cene	Oligo- cene	Mio- cene	Plio- cene
New York	+		⊕	⊕⊕|⊕|	⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|⊕|									

Gas, +, Oil, O. Both, ⊕. Chief production, —.

One of the astonishing facts about the source of oil is that the Paleozoic is productive only in the United States and Canada (with the exception of some extremely minor quantities found in the Paleozoic in Great Britain and Russia). Throughout the rest of the world, the oil comes from the Cretaceous and Tertiary formations.

The geologic formations that are at all productive in each state in the United States are shown in Table 85.

OIL AND GAS FIELDS OF THE UNITED STATES

The oil and gas fields in the United States are distributed from the Appalachian region to the Pacific Coast (see Fig. 182). They can be best studied by grouping the states containing pools or minor fields into major fields to which, through common usage, names have been



Fig. 182.—The oil and gas fields of the United States in 1929

assigned. These major fields are the Appalachian field (Pennsylvania, New York, West Virginia, Ohio, Kentucky, Tennessee, Alabama); Michigan field; Lima (Ohio)-Indiana field; Illinois and southwest Indiana field; Mid-Continent field (Oklahoma, Texas, Kansas, Louisiana, Arkansas); Gulf Coast field (southern Texas and Louisiana); Rocky Mountain field (New Mexico, Colorado, Utah, Wyoming, Montana); and California field. Figure 183 illustrates the relative importance of these major fields. Figure 184 shows the rank of the individual states in oil production.

The oil within these large fields is roughly of the same general character. There is also some similarity in the general geology within a field. No attempt is made in this volume to give the detailed geology of the oil fields. Such information can be found in more detailed books on oil geology.

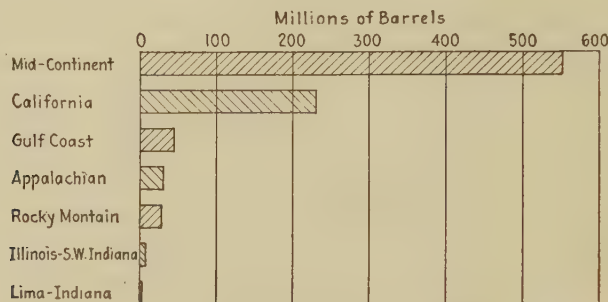


FIG. 183.—Production of oil, by fields, in the United States in 1928. (*U. S. Mineral Resources, 1928, Part 2.*)

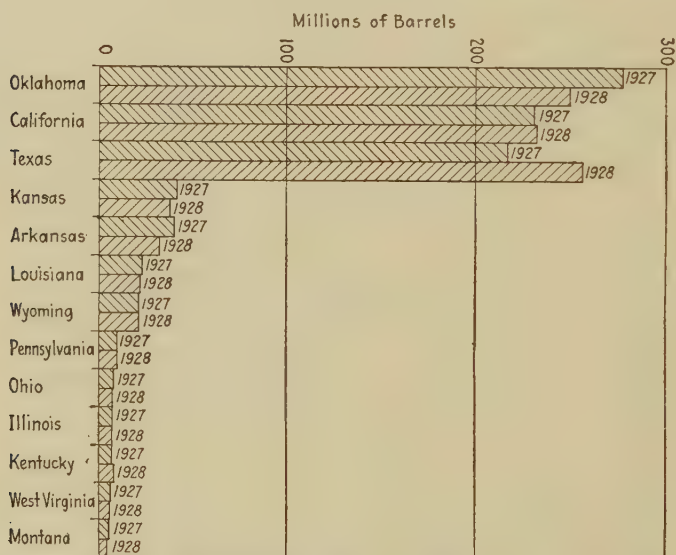


FIG. 184.—Production of petroleum in the United States, by states, in 1927 and 1928. Note the enormous total production of the three leading states. (*Data from U. S. Mineral Resources.*)

THE APPALACHIAN FIELD

The first oil well drilled in the United States was in the Appalachian field in 1859. The early history of oil in this country is, therefore, the history of the Appalachian field and has been given in some detail at the beginning of this chapter. The Appalachian field includes parts of several states, but the producing area contains only about 3,500 square miles. The major production has come first from Pennsylvania, secondly

from West Virginia. The field dies out in central Ohio to the west and in Alabama to the south.

Pennsylvania and West Virginia.—The principal production in Pennsylvania and West Virginia comes from the Devonian formation, in which there are 22 producing sands. The chief of these are in the Chemung and Catskill formations (Upper Devonian). They lie from 1,900 to 3,770 feet below the Pittsburgh coal, which is at variable depths below the surface. There are 15 producing sands in the Carboniferous formation (they are distributed through the Mississippian and Pennsylvanian) all but one of which lie below the Pittsburgh coal. The most productive single pool in the Appalachian field is the Bradford pool in McKean County, Pennsylvania. It covers 85,000 acres, or 13.28 square miles. The Bradford is both the largest and the oldest pool in the United States.

New York.—The chief oil production in New York comes from Chemung beds of Devonian age, and a little comes from the Silurian. Some gas has been found in the underlying formations, down to and including the Potsdam beds in the Cambrian.

Ohio.—The producing area of Pennsylvania continues westward into eastern Ohio, where the production, unlike that in Pennsylvania, comes largely from the Mississippian and Pennsylvanian formations. The pools in Ohio are all small; and the area long ago reached its maximum production, in spite of the thousands of wells that have been drilled more recently. The Clinton sand (Silurian) produces enormous quantities of gas in a belt that extends roughly north and south through central Ohio. This sand has been called the world's greatest gas producer. The Clinton may contain gas or oil in western Pennsylvanian, but it lies so deep there that it has not been reached by the drill.

Other States.—The Appalachian field also includes Kentucky, Tennessee, and Alabama; but Kentucky is the only one of these states that has made an important production. Its oil comes chiefly from the Devonian and Mississippian formations; but those above, and even those below, have produced a little. Limestone is a common reservoir rock in Kentucky. Most of the small amount of oil produced in Tennessee comes from Ordovician rocks. Alabama has produced only gas, which is found in the Pottsville formation (Pennsylvanian).

Structures of the Appalachian Field.—The structures of the Appalachian field are strong in Pennsylvania but become less marked in all directions away from it, having changed to relatively gentle folds and broad, gently dipping areas in other states. Oil is found, as a rule, where the dips are less than 3°, though rarely they may be 10°. It is estimated that 85 per cent of the pools are in rocks dipping 1° or less. The important producing areas are singularly free from faults; but in Kentucky, Tennessee, and Alabama faults are more common.

Character of the Oil and Gas.—The Appalachian oil has a paraffin base and is of a very high grade. Its average value per barrel in 1927 was \$2.52. The average price for petroleum in the United States was \$1.30. The gasoline content of the natural gas of the Appalachian field is low: less than 0.4 gallon per 1,000 cubic feet of gas. Nevertheless, over half of the gas is treated to recover its gasoline.

THE MID-CONTINENT FIELD

The Mid-Continent field is the most important oil-producing area in the United States. Although it produced some oil and gas as early as 1889, its real importance dates from 1903 when the yearly production first reached 1,000,000 barrels. Twenty-five years later, the annual production in the Mid-Continent field was 645,300,000 barrels of oil. This field has produced about 27 per cent of the world's petroleum. The Glenn pool, southwest of Tulsa, Oklahoma (discovered in December, 1905), was the first important pool in the area, but the discovery of others followed rapidly.

The Important Pools.—Notable pools are the Cushing, Seminole area, Glenn-Kiefer, Burbank, Healdton, Tonkawa, Garber, and Oklahoma City in Oklahoma; the Butler County, Augusta, and Eldorado in Kansas; the Electra, Burkburnett, Humble, Mexia, Powell, Panhandle, and West Texas in Texas; the Caddo in Louisiana; and the Smackover in Arkansas.

Producing Formations.—The oil of all these areas comes mainly from the Pennsylvanian and Lower Permian formations. That of the Permian horizons has migrated into them from those of the Pennsylvanian. Deeper drilling has resulted in the production of considerable oil from the Mississippian formation (both from limestones and sands) and an immense production from the Wilcox sand (also the Burgen and Tyner sands) in the Ordovician formation. This oil is generally regarded as having migrated downward into the Ordovician from the Chattanooga or Woodford shales above. The oil in the newly discovered Oklahoma City pool comes from the Arbuckle limestone and "detrital" sand, of Ordovician age. Its source is in doubt. The oil in the Caddo (Louisiana) field comes mainly from the Woodbine sand at the base of the Upper Cretaceous. The Smackover (Arkansas) field also produces from the Cretaceous. The field of western Texas produces its oil from Ordovician and Permian formations. Some believe that the oil migrated into the Permian beds from those of the Pennsylvanian, but others think that it originated in the Permian.

Structures.—The structures of the Mid-Continent are less well defined than those of the Appalachian field. The Pennsylvanian rocks dip gently westward in Kansas and Oklahoma. This general western dip is broken in north-central Oklahoma and throughout central Kansas

by the Nemaha granite ridge, which strikes slightly northeast and extends into Nebraska. Drilling for oil and gas revealed the presence of this buried ridge.

The productive structures of the Mid-Continent field are usually small elongated or irregular domes, having low dips on the sides. These low dips are commonly broken by terraces. Many of the dips average 50 feet per mile or less. As a rule, there is little evidence of relationship between the structures. In some areas, as in Osage County, Oklahoma, the rocks are very much broken by faults, and the dips are in all directions. Structures which owe their origin to the shape of buried topographies developed by erosion between periods of deposition have been recognized in southern Oklahoma and probably in the Panhandle of Texas. Some of the pools in central Oklahoma may be on such structures. In north-central Texas, the oil occurs mainly in terraces on a broad, low anticlinal structure covering a very large area. An occasional pool (the Electra, for example) shows an anticlinal structure. The central Texas area lies on the Bend arch, and the pools occur on anticlinal or monoclinal modifications of the arch. The Caddo (Louisiana) pool is on the north side of a broad, low arch. This same type of structure occurs in the Texas Panhandle and in the Permian basin of western Texas, though well-marked structures appear to be more common throughout west-central Texas. The rocks of the Mid-Continent field are generally filled with water, a fact which is probably of great importance in causing the oil to occupy the less-marked structures of the region.

Character of the Oil.—The oil of the Mid-Continent field is of an excellent grade. It contains a high percentage of gasoline, kerosene, naphthas, and lubricating oils; some paraffin; and a residue of high-grade fuel oil (see Table 72, p. 386). Certain of the oils have been of exceptional grade, but others, which contain considerable sulfur, are of less value. Some of the West Texas oils are about 30° A. P. I. and are high in sulfur.

Gas in the Mid-Continent Field.—The Mid-Continent field is the greatest gas-producing area of the United States. It produced over 800,000,000,000 cubic feet of gas in 1927, or over 55 per cent of the total production in the United States. This gas is rich in natural-gas gasoline, and over 670,000,000 cubic feet of it was treated that year to recover the gasoline. The Oklahoma gas was the richest, with a yield of 2.1 gallons per 1,000 cubic feet of gas. Some of the gas fields in Kansas and Texas contain helium.

THE CALIFORNIA FIELD

California became a producer of oil in 1876, but it was not until 1895 that the annual production reached 1,000,000 barrels. Ten years later, the yearly production was 33,000,000 barrels; in another decade,

it had risen to 86,000,000; and in 1928, to 231,982,000. The California field contributes annually from 25 to 30 per cent of our oil.

TABLE 86.—DATA ABOUT CALIFORNIA'S OIL POOLS¹

Field	Date of discovery	Total production to November, 1928, bbls.	Proved acreage	Recovery per acre, bbls.	Producing wells	Average number of acres per well
Kern River.....	1899	269,679,952	9,000	29,964	1,167	8
Mount Poso.....	1926	82,066	1,500	55	4	375
Fruitvale.....	1928	30,200	500	60	2	250
Round Mountain.....	1927	46,131	750	62	2	375
McKittrick.....	1898	76,822,971	2,100	36,582	288	7
Midway-Sunset.....	1900	637,415,706	45,000	14,165	2,539	18
Elk Hills.....	1919	99,927,092	5,000	19,985	207	24
Lost Hills-Belridge.....	1910	58,305,352	4,600	12,675	307	15
Coalinga.....	1896	308,282,221	16,500	18,684	789	21
Wheeler Ridge.....	1923	1,814,754	225	8,065	34	7
Watsonville.....	1880	1,233,388	100	12,334	7	14
Santa Maria.....	1902	123,090,488	8,250	14,920	227	36
Summerland.....	1894	2,719,052	150	18,127	89	2
Elwood-Goleta.....	1927	281,964	250	1,128	4	63
Rincon.....	1927	679,133	50	13,583	20	2
Ventura Avenue.....	1912	57,955,518	1,750	33,117	130	13
Ventura-Newhall.....	1870	43,178,802	4,000	10,795	517	8
Los Angeles-Salt Lake.....	1894	61,858,185	1,500	41,239	325	5
Whittier.....	1912	13,361,813	700	19,088	170	4
Fullerton (Brea Olinda).....	1897	126,571,915	1,800	70,323	379	5
Coyote.....	1912	114,962,901	2,150	53,471	210	10
Santa Fe Springs.....	1921	179,309,168	1,800	99,616	293	6
Montebello.....	1917	79,133,891	1,500	52,756	170	9
Richfield.....	1919	53,625,387	1,500	35,750	267	6
Huntington Beach.....	1920	141,890,306	2,800	50,675	566	5
Long Beach.....	1921	305,031,906	1,750	174,304	800	2
Torrance.....	1922	57,781,121	5,000	11,556	618	8
Dominguez.....	1923	37,302,494	1,000	37,302	73	14
Rosecrans.....	1924	19,308,754	500	38,618	109	4
Inglewood.....	1924	56,712,675	900	63,014	220	4
Newport.....	1900	86,482	100	865	2	50
Seal Beach-Alamitos.....	1926	26,855,711	1,250	21,484	134	9
Protrero.....	1927	70,344	100	703	1	100

¹ STOCKMAN, Phenomenal Growth of the California Field, *Oil and Gas Jour.*, vol. XXVII, p. 81, Nov. 29, 1928.

Important Pools.—The California pools are found mainly in two areas: one, near the coast in southern California; the other, around the

southern end of the San Joaquin valley in the south-central part of the state. The chief pools along the coast are in the following counties: Orange (Coyote Hills and Fullerton); Santa Barbara; and Los Angeles (Montebello, Salt Lake, Puente-Whittier, Signal Hill or Long Beach, Santa Fe Springs, and Huntington Beach). These pools produced 172,000,000 barrels of oil in 1927. In the San Joaquin valley, which produced 59,000,000 barrels in 1927, the important pools are the Midway-Sunset, Coalinga, Elk Hills, Kern River, McKittrick, and Lost Hills.

California has no less than 33 pools the total production of which to the middle of 1928 amounted to 2,955,417,843 barrels, or about 20 per cent of the world's total production to that time. Table 86 gives much interesting information about the individual pools in the state.

Age of Oil Formations.—The oil is found in sandstones which are associated with organic shales. These shales contain an abundance of organic remains, mainly diatoms (see Fig. 153, p. 395). The sands above the shales are the most productive. Both sands and shales belong to the Eocene and Miocene horizons of the Tertiary and, to a lesser extent, the Upper Cretaceous. Much interest attaches to the occurrence of the oil in the Tertiary, for it was the study of these formations that furnished Arnold, Anderson, Pack, and others with the first conclusive evidence that the oil in California was of organic origin. These men had been able to trace the source of the oil in the sands to the diatomaceous shales of the Tertiary; and, as before stated, their discovery has been ably supported by the research of Tolman and others.

Structures.—The structure of the rocks in the California field is very complicated, but the excellent exposures throughout much of the area have been a great aid in unraveling it. The marked folding and faulting, the numerous unconformities, and the lenticular character of the sands have given rise to many types of reservoirs. The oil occurs in all these varied structures and is sometimes confined by the sealing up of the outcrop of an oil-bearing sandstone by asphalt (locally called "brea"). Although most of the oil occurs in sands, a fissured shale is the reservoir rock in one field. Some producing zones are extraordinarily thick, those at Signal Hill totaling nearly 3,000 feet.

Character of the Oil.—The oil of the California field is not of a grade so high as that of the eastern fields (excluding the Gulf Coast field), as it contains more asphalt and less gasoline, kerosene, and lubricating oils. It is widely used as a fuel oil. All oil that contains any of the lighter products is treated to remove them.

California as a Gas Producer.—In the early part of the century, California produced but little gas, but the production climbed steadily until in more recent years it has been third in the United States. The Midway field in Kern County is the largest producer. Its gas comes from

wells 2,100 to 3,000 feet deep. Gas is also produced in the Whittier-Fullerton field in Orange and Los Angeles counties.

ILLINOIS FIELD

The Illinois field began to produce oil in the late eighties, but it was not until 1905 that the amount was significant (181,000 barrels). The next year, 4,397,000 barrels was produced, and the production continued to rise until 1910, when it reached a maximum of 33,000,000 barrels. Since then, it has gradually declined. The producing area in Illinois is mainly in the southeastern part of the state, in Crawford, Lawrence, Wabash, Clark, and Cumberland counties. A few small pools are in the west-central part. The oil is mainly a paraffin oil but contains some asphalt and a little sulfur.

Age of Oil Formations.—The oil in Illinois comes from the Pennsylvanian and the upper part of the Mississippian formations, save in the Colmas field, McDonough County, in the western part of the state, where it comes from a sand at the base of the Niagaran (Silurian). There are several sands, ranging in depth from 450 to 2,000 feet.

The Structures.—The pools of southeastern Illinois are found in domes along a large anticline (the La Salle), which strikes northwest and southeast across the above-mentioned counties.

THE ROCKY MOUNTAIN FIELD

The chief producing states in the Rocky Mountain region are (in order of production) Wyoming, Montana, Colorado, and New Mexico. Considerable test drilling is being done in Utah.

Colorado.—Colorado's first production of oil was in 1887 from the Florence field. Five years later, it reached its maximum production and since then has steadily declined. Essentially all of Colorado's production has come from the Florence field. This field is unique in having a synclinal structure and in producing the oil from a fractured shale (see Fig. 155, p. 408). Several small areas in the state make a small annual production.

Wyoming.—Wyoming began to produce oil in 1894, but the production was insignificant until 1912, when it jumped to 1,500,000 barrels. Since then, it has steadily increased. There are a number of pools in the state, but most of the production comes from six, of which, one, the Salt Creek, has furnished 70 per cent of the state's total production. This field (of political notoriety on account of the Teapot dome) was the first real producer in Wyoming. The Shannon fields in Natrona County, about 50 miles north of Casper, are also important. Other pools occur in the Bighorn basin, and active drilling is going on in all favorable parts of the state. Over 100 structures (anticlines and domes) have been

located in Wyoming, but only 23 have shown any production. Only the most promising structures have been drilled.

Montana.—The oil production in Montana is mainly from the Kevin-Sunburst and Cat Creek pools. Small productions come from several scattered pools none of which is especially important. The Cat Creek field is in central Montana, and the Kevin-Sunburst is on the Sweetgrass arch in the north-central part of the state.

New Mexico.—New Mexico's oil production comes from two widely separated areas: one, in San Juan County in the northwestern part of the state (the Rattlesnake and Hogback pools); and the other, in the southeastern corner, a few miles east of Artesia in Eddy County. The oil comes from Cretaceous rocks in San Juan County and is of exceptionally high grade, ranging from 56 to 64° A. P. I. The Eddy County oil comes from the Permian formation and is 37° A. P. I. gravity.

Age of Oil Formations of the Rocky Mountain Field and the Character of the Oil.—The major production of the Rocky Mountain field comes from the Cretaceous formation or from the other Mesozoic formations underlying it. The oil is a high-grade paraffin oil and has an excellent content of the lighter oils. Some is produced from the Carboniferous formations, but it is a heavy asphaltic oil of little value save for fuel. The oil of Artesia, New Mexico, from the Permian is of good grade.

Structure of Formations in the Rocky Mountain Field.—The structures in the Rocky Mountain area are well-marked anticlines. Some are faulted. There are a large number of structures, but only about half have so far proved to be productive, and many of these only on a small scale.

THE LIMA-INDIANA FIELD

The second important oil field to be developed in the United States was the Lima-Indiana field lying in northwestern Ohio and northeastern Indiana. It was opened in 1886 and in 10 years was producing 25,000,000 barrels per year, which was within 9,000,000 barrels of the yearly production of the Appalachian field at that time. The Lima-Indiana production declined for a period, then in 1904 it mounted to nearly the original maximum, and since that time has declined rapidly. In 1928, the production was 1,677,000 barrels. Ohio has produced the greater part of the oil.

Age and Structure of Oil Formations.—The oil is produced from the Trenton dolomite (Ordovician) through wells that have a maximum depth of 1,500 feet in Ohio and 1,000 feet in Indiana. The field is located on a broad, low anticline. The chief producing horizon is evidently a water-channeled zone lying about 50 feet below the top of the dolomite.

Character of Oil.—The oil is heavier in grade than that of Pennsylvania and, in addition, contains sulfur, although it has a paraffin base. When the wells were first brought in, it had very little market value and at one time was worth only 15 cents a barrel.

THE GULF COAST OR SALT DOME FIELD

The Gulf Coast field includes the part of Texas and Louisiana that lies along the Gulf of Mexico. Within this area, most of the pools are associated with salt domes. There is little topographic evidence of the domes, as they are usually only a few feet above the surrounding surface and may be at the same level. They rarely include more than a few hundred acres. The famous discovery pool, the Spindletop, covered 225 acres.¹ Inside a year and a half, 280 wells had been drilled in this area, and as a result the pool was soon drained. In 1926, deep drilling revealed a productive sand and added about 40 acres to the area of the pool. Other pools were soon discovered in some of which gushers producing 75,000 barrels were found, but all have been short-lived (see Fig. 164, p. 414). Farther to the southwest, along the coast, there is an important gas field, which apparently is unconnected with salt domes. Some very large gas wells have been discovered in this region in the vicinity of Corpus Christi.

The Oil Formations.—The oil usually occurs in porous limestones or dolomites but also in sands. Below the oil-bearing rock, gypsum, sulfur, and salt are usually found. The salt may exceed 2,000 feet in thickness and covers an area about the size of the pool. The rocks of the area are of Tertiary age, but it is not known whether the oil comes from the Tertiary or from the deeper-lying Mesozoic and Paleozoic beds.

Structure.—The reservoir rocks may lie essentially flat over the salt column, or they may be dome shaped. The beds along the sides of the column dip away at varying angles. This upturning of the beds is believed to be due to the upward thrust of the salt column.

Character of the Oil.—The salt domes produce asphaltic oils many of which are of low grade. Essentially all contain considerable sulfur or hydrogen sulfide. Any light oils they contain are extracted, and the residue is used in the manufacture of asphalt or as a fuel oil.

MICHIGAN FIELD

Michigan has been a small producer of oil for many years. Recently, new fields have been found near Saginaw and Muskegon, which are being rapidly developed.

OIL IN OTHER STATES

A small quantity of oil and gas has been found in the vicinity of Kansas City, Missouri. This has been Missouri's only production. An occasional wildcat well has shown oil in limited amounts in some other states, but to date (1929) no important developments have been made.

¹ Figures as to area of Spindletop field do not agree.

THE FOREIGN OIL FIELDS

The growing market for oil and its products in all parts of the world has greatly stimulated the search for it. Since 1900, no less than 14 countries have become producers, whereas before that date only 11 (including the United States) were producing. The location of the important oil fields of the world is shown on the map of Fig. 185. In the following brief notes, the most important foreign oil fields are taken up in the order of their chronological development.

Rumania.—The Rumanian oil fields are the oldest in Europe and are said to have been producing since 1857, two years before oil was discovered in the United States. The wells occur in a belt about 20 miles wide, that extends east along the south side of the Transylvanian Mountains nearly to Buzeu and then swings north along the east side of the Carpathian Mountains. The producing formations are of Miocene age and consist of sands and marls. The entire belt has been much folded and faulted. Recent developments sent the production to its peak of about 28,000,000 barrels in 1928.

Canada.—Canada's first production of oil was in 1862; and, although the total has never reached 1,000,000 barrels annually, the production has been steady. The oil is produced in Ontario and Alberta. That of Ontario comes from the Devonian limestone. The structures are well defined, but all have low dips. In Alberta, the important field is near Edmonton, where the oil and gas come from the Cretaceous formation. Numerous oil seeps occur throughout Alberta and adjacent provinces. The region north from Alberta to the Arctic Ocean shows some indications of oil and, in spite of the difficulties encountered there, is being explored.

Russia.—The great Baku oil field of Russia is on a peninsula extending from the east end of the Caucasus Mountains out into the Caspian Sea. There are two main areas. One contains about 2,000 and the other 1,000 acres. Most of the oil comes from Miocene formations, but some from the Oligocene. Gushers of 50,000 to 100,000 barrels have been common. The oil sands are very loose, and, as a result, 20 to 30 per cent of the material discharged is sand. This has accumulated in great piles about the derricks. The structure is a typical anticline. The estimated production of the field in 1928 was 80,000,000 barrels, a production exceeded only in 1901 and 1902.

Galicia (Poland).—The Galician oil fields lie north of the Carpathian Mountains. There are two fields, but both are relatively small. The oil comes from the Cretaceous to the Miocene. The major part is from the Eocene. The region is so intensely folded and faulted, that drilling is very difficult and slow. A well 4,000 to 4,500 feet deep requires 3 to 4 years for completion.

Japan.—The Japanese oil fields are along the shore of the Sea of Japan. The oil is produced from Tertiary sandstones and tuffs that are interbedded with shales. It is found associated with anticlines.

Germany.—The only oil field in Germany is a small one, near Hanover, in the northwestern part of the country. The oil is found in Jurassic sandstones and limestones.

Burma (India).—The chief oil district in India is the Irrawaddy in upper Burma. Others are the Assam and Punjab. There are two fields in the Irrawaddy: the Yenangyaung and the Yenangyat-Singu. They cover about 1,000 acres. The oil is found in the Miocene formations on long, sharp anticlines.

Dutch East Indies.—The oil fields of the Dutch East Indies are scattered over Sumatra, Java, and southern Borneo. The oil is found in Tertiary beds, mainly those of the Miocene and Pliocene. The anti-



FIG. 186.—Curve showing Mexico's oil production. (Data from U. S. Mineral Resources.)

clines are quite sharp. The production of the islands places them among the first ten producing countries.

Peru.—The Peruvian fields are in the extreme northwestern part of the country along the seacoast. There are three fields, all close together, and all producing from anticlines that are more or less faulted. The oil-bearing formations are of Tertiary age.

Mexico.—Mexico did not become an important producer of oil until 1908. The production rapidly climbed to 193,000,000 barrels in 1921 and since then has declined to about one-fourth that amount (Fig. 186). It comes largely from two fields: the northern, about 35 miles west of Tampico; and the southern (or "Golden Lane" as it is called), to the west and north of Tuxpam.

The northern field contains several important pools. The oil is produced from a zone of fractures in an otherwise non-porous limestone. This rock is about 500 feet thick and occurs in the top of the Comanchean limestone (Tamaulipas) and the lower 250 feet of the San Felipe limestone (Cretaceous).

The Golden Lane or southern field is famous for its enormous gushers and its tremendous production from individual wells. The producing area is a curved belt about 50 miles long and 2 miles or less in width. The oil comes from the porous and channeled Tamasopa limestone which is correlated with the Comanchean limestone of the northern field. The limestone is capped by the hard limestone or shales of the San Felipe formation.

The great gusher, No. 4, of the Huasteca Petroleum Company, in the Cerro Azul pool has produced over 80,000,000 barrels of oil. Well No. 4 in the Potrero del Dano pool has produced 100,000,000 barrels of oil. Salt water has always been abundant in the southern field, and care has to be exercised to prevent a well's going entirely to water in its early history. The pools in this field have rapidly declined; and, although there has been much drilling, no new productive areas have been discovered. The number of dry holes is over 50 per cent for most areas.

Argentina.—The oil fields of Argentina are in the southern part along the sea and in the northwestern part along the Andes Mountains. The southern area, the Comodoro Rivadavia, is the most important and has steadily increased in production since its discovery in 1907. The oil comes from beds near the top of the Cretaceous formation. Tertiary beds unconformably overlie the Cretaceous. The wells are about 1,800 feet deep. The major structure is a very flat monocline. Slight reversals of dip control the accumulation of the oil. Active prospecting in northwestern Argentina may lead to the discovery of oil in paying quantities.

Trinidad.—The island of Trinidad was the first place in the Americas where one of the hydrocarbons was noted and described, for it was the famous Pitch Lake (now an important source of asphalt) in the southwestern part of the island that Sir Walter Raleigh described in 1595.

The southern half of the island, where the oil pools occur, is underlain by Cretaceous and Tertiary rocks. During the last 20 years, there has been considerable development of the field. The oil occurs mainly in Tertiary formations and is a low-grade fuel oil. An excellent paraffin oil has recently been found in the top of the Cretaceous. The pools are all located on well-defined anticlines, and the oil is recovered from depths as great as 2,000 feet.

Egypt.—Egypt became a producer of oil in 1911. It reached its maximum production 7 years later and since then has maintained a production of over a million barrels annually. There are two producing fields, which lie about 35 miles apart. Both are located southeast of Cairo near the head of the Red Sea. The most important field, the Hurgada, produces from a dome in Cretaceous beds. The oil of the other field comes from Miocene beds in the Tertiary formation. Gypsum and salt are associated with the oil in both fields.

Persia.—The rapid development of the Persian fields has been exceeded only by the development of remarkable pools in the United

States and Venezuela. Production began in 1910, reached 1,857,000 barrels in 1913, and mounted rapidly to nearly 40,000,000 barrels in 1927. The presence of oil had long been known in Persia, but little had been done to develop it until 1909. The production is mainly from fields near Shuster, 100 to 125 miles from the Persian Gulf, though oil seeps are numerous throughout the southwestern part of the country. The Maidan-i-Naphtun field is the most important and has had many big gushers. The oil comes from Miocene beds having a well-defined anticlinal structure. The reservoir rock is a very porous, shelly limestone.

Much has been said about the enormous reserves of oil in Persia. The opinions are based upon the presence of many anticlinal structures and seeps. Neither of these features, however, constitutes a secure basis for assuming the presence of large reserves of oil. Continued develop-

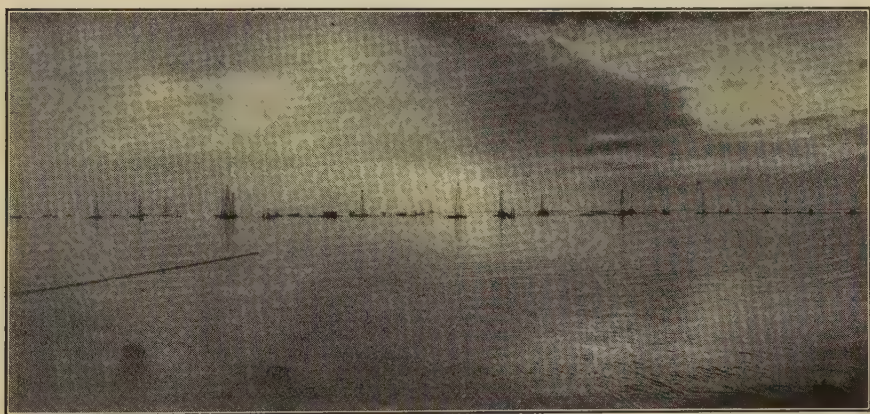


FIG. 187.—View (looking west) of the Ambrosio oil field on the east shore of Lake Maracaibo, Venezuela. The wells range in depth from 1,200 to 3,000 feet and produce from 500 to 3,000 barrels per day. (Photo. by V. W. Vandiver.)

ment, only, will determine the productivity of most of these structures and check up the potentiality of the region for oil.

Sarawak (in British Borneo).—The producing oil field in Sarawak is at Mire on the western coast. Production began in 1911 and had reached nearly 5,000,000 barrels in 1927. The oil is heavy (18.39° A. P. I.). It comes from upper Tertiary rocks.

Algeria.—There are numerous surface indications of oil in various parts of Algeria; but, although wells have been drilled in both Tertiary and Cretaceous formations, no developments of importance have been made.

Ecuador.—The Tertiary rocks along the coast have furnished the only oil so far found in Ecuador. The Santa Elena field is the most important one; and, due to considerable recent drilling, its production has reached about half a million barrels. The field is a continuation of the Peruvian fields to the south.

Venezuela.—The oil prospects of Venezuela are excellent, and therefore drilling is being carried on in all the favorable areas. Production began in 1917, but since then the country has reached second place among those producing oil, in 1928 passing both Russia and Mexico. In that year, Venezuela's output was 105,000,000 barrels, which was 8.5 per cent of the world's production. The chief productive area is not only around



FIG. 188.—Gas gusher in well 148 of the Lago Petroleum Corporation, Punta Benitez oil field on the east side of Lake Maracaibo, Venezuela. This well blew in at 1,350 feet with 20,000,000 cubic feet of gas in 1928. It was plugged through a relief well 300 feet away, and drilled in as a 400-barrel oil well at 2,000 feet. (Photo. by V. W. Vandiver.)

but also extends under Lake Maracaibo (Figs. 187 and 188). The productive area has been extended to the eastern part of Venezuela. The oil is found in Tertiary beds and is associated with only moderately well-defined structures.

France.—There is only one productive area in France. This is in the department of Bas Rhin in Alsace. The oil comes from Oligocene beds in the Tertiary formation. The field is unique in that about 40 per cent of the oil comes from mines. These mines are about 720 feet deep. The total production from wells (500 of them) and from the mines is about 1,000 barrels per day.

England.—England has very limited possibilities for oil. The present producing areas are in central England (Derbyshire and Staffordshire). The small production in Derbyshire comes from the Mississippian formation, from wells about 3,000 feet deep.

Czechoslovakia.—There are two small oil-producing areas in Czechoslovakia, one near the eastern and the other near the western part of the Carpathian Mountains. The oil is in beds of Tertiary age.

Colombia.—The main oil-producing area in Colombia is in the Infantas field in the department of Santandar. It is apparently a continuation to the southwest of the important producing area around Lake Maracaibo in Venezuela. Both Cretaceous and Tertiary rocks underlie the productive area, but the chief producing horizon is the Eocene. The oil is

found in well-defined anticlines. The production has climbed to 20,000,-000 barrels since 1922.

Mesopotamia (or Iraq).—Lying to the west of the producing area in Persia, Iraq attracted the attention of oil producers, and recent developments have shown that it has considerable possibilities for oil. The geology is similar to that of Persia, and well-defined structures are reported to be common.

Other Countries.—Wherever surface indications of oil have been found, more or less explorative work has been done. Small quantities of oil are produced in some of the localities, which are scattered over all the continents. Their combined production is a few thousand barrels annually.

USES OF OIL AND GAS

The dominant use of oil and gas is to produce energy, which man directs to many purposes. Petroleum may be used without refining as a fuel oil, lubricating oil, or on roads; but the larger part of it goes to the refineries for treatment. Even natural gas (formerly used as soon as it could be made to reach the consumer) is now treated, first, to remove the gasoline it contains and, then, to recover any rare gas, such as helium.

Products of Refined Petroleum.—The refining of petroleum is a long and complicated process that results in a great many products. These products and their uses are shown in Table 87.

Refining Petroleum.—If the oil as it comes from the well contains water, it is allowed to settle out. The crude oil is then run into horizontal stills made of steel and is heated to a temperature which varies with the character of the crude oil and the product desired. The lighter oils, such as benzene, gasoline, naphthas, and kerosene, are driven off at low temperatures (150°C. and above). To secure the higher compounds, the temperature is raised to the point needed. The final product may be either liquid or solid. As each distillate is driven off, it is passed through a coil of water-cooled pipe, and the condensed product is cleaned by sulfuric acid and caustic soda and finally is washed with water. The distillate may be redistilled to secure products of a special gravity.

Great progress has been made in refining methods during the last decade. One of the most important improvements has been the development of cracking stills, by means of which the production of gasoline from a crude oil is greatly increased. The average yield, 10 years ago, was from 25 to 30 per cent gasoline, but the cracking stills have increased this amount to 60 per cent or more. The fact that oils which heretofore yielded low quantities of gasoline are now contributing large amounts is of much significance in oil conservation.

TABLE 87.—THE VARIOUS PRODUCTS RECOVERED IN REFINING PETROLEUM AND THEIR CHIEF USES¹

Major product	Subproducts	Uses
Hydrocarbon gases	Natural gas	Fuel
	Natural gasoline	Blending with refinery gasoline Motor oil Aviation fuel
	Carbon black	Paint Ink Rubber tires
	Liquefied gases	Coal-gas enrichment Refrigeration Chemical synthesis
Light distillates	Gasoline	Motor fuels General solvents (commercial solvents)
	Napthas	Dry cleaning Paints Soap manufacture
	Kerosene	Tractor fuel Heating Illumination
Intermediate distillates	Gas oil	Diesel fuel Cracking stock Coal-gas enrichment
	Absorption oil	Gasoline recovery Benzol
Heavy distillates	Lubricating oils	Internal-combustion machines Industrial uses
	Technical oils	Mechanical Emulsifying
	Waxes	Candles Waterproofing Sealing
Residual oils	Cylinder stocks	Bright stocks Steam cylinder oils Grease compounding
	Fuel oil	Boiler fuel Furnace fuel Gas manufacture
	Greases	Heavy lubrication
	Asphalt	Paving Roofing Paints
	Coke	Fuel Carbon products Graphite
Sludge products	Acids	Source of valuable chemicals

¹ Data from an article by H. W. Camp, *Oil and Gas Jour.*, vol. XXVI, No. 41, p. 105, 1928.

Oil as a Fuel.—Petroleum is an excellent fuel, as the heating values for various fuels given in the table below show:

TABLE 88.—THE HEATING VALUE OF THE VARIOUS COMMON FUELS, EXCLUDING GASES

Fuel	B. t. u. per pound
Heavy Pennsylvania petroleum.....	19,210
Petroleum of Spindletop, Texas.....	19,785
Coal (average of many).....	13,500
Coke.....	11,700
Peat.....	8,100
Wood.....	5,040

The ease with which oil may be handled and stored is a consideration in its use. The domestic oil consumed in 1925 in the United States constituted 21.3 per cent of the total heating value of all fuels used, and if the natural gas and imported oil used are included, the percentage would be 28.9, or nearly one-third of the heating value of all fuels used.

The United States government has withdrawn public lands in oil fields in order to secure a reserve of fuel oil for the navy, which shows that oil is preferred for fuel on sea as well as on land. It is estimated that between 700,000 and 800,000 private homes in this country will be heated by oil by the end of 1928.

Synthetic Organic Compounds from Petroleum.—A field of research that offers great possibilities is the development of synthetic organic compounds from petroleum. Many of these would be by-products. As illustrative of the character of this field, Table 89 has been prepared from material presented by H. W. Camp.

Other Uses of Oil.—Other uses of oil products are shown by table 89. The number of automobiles in this country (over 25,000,000 in 1929) gives some idea as to the enormous amounts of gasoline used in internal-combustion motors. In 1928, the total consumption of gasoline in the United States, and the exports of the same, were 390,000,000 barrels, and this figure will probably reach 425,000,000 barrels in 1929. The use of kerosene, lubricating oils, paraffin, and innumerable other products further indicates the close association of modern life with petroleum (a product of *former* life).

Use of Natural Gas.—Natural gas is an ideal fuel. Although there are some commercial gases that have a higher heating power, they cannot for other reasons compete with the natural product (see Tables 77 and 78, pp. 391 and 408). Natural gas is piped hundreds of miles to the consumer. In 1926, there were 3,731,000 domestic consumers of natural gas in this country. The average cost of this gas to the consumer was \$0.581 per 1,000 cubic feet that year, and it is of interest to note that the average cost of the gas at the wells was only \$0.097 per 1,000 cubic feet. Over 420,000,000,000 cubic feet of gas was used in field operations in the oil

TABLE 89.—ORGANIC COMPOUNDS PRODUCED FROM PETROLEUM AND THEIR USES¹

Classes	Compounds in each class	Uses
Alkyl chlorides	Methyl chloride Ethyl chloride Carbon tetrachloride Chloroform, and others	Refrigerants Solvents Anesthetics Base for further chemical synthesis
Alcohols	Methyl Ethyl Propyl Butyl Amyl Higher alcohols, and others	General solvents Rayon silk industry Pyroxylin lacquer industry
Aldehydes	Formaldehyde Acetaldehyde, etc.	Manufacture of synthetic resins Antiseptics, and denaturants Base for synthesis
Esters	Propyl acetate Amyl acetate Butyl acetate	Base for pyroxylin lacquers Base for chemical synthesis
Fatty acids	Formic, etc.	Undeveloped at present; but edible fats, butter and lard substitutes, and soap are possible from petroleum synthesis
Keytones	Acetone Methylethel, keytones, etc.	Solvents Base for chemical synthesis
Aromatics	Benzol Toluol, etc.	Dyestuffs Saccharin Explosives Antiseptics Perfumes Certified leather, etc.

¹ Data from article by H. W. Camp, *Oil and Gas Jour.*, vol. XXVI, No. 41, p. 105, 1928.

fields. Slightly more than this was used for industrial purposes. Over 175,000,000,000 cubic feet of natural gas was used in the manufacture of carbon black, which is a sooty substance made by burning natural gas with oxygen in amounts insufficient to produce complete combustion. The average price per pound for carbon black in 1928 was \$0.055, and since an average of 1.42 pounds is produced from 1,000 cubic feet of gas, it is readily seen that only a very cheap gas could be used. The average value of natural gas at points of production in Louisiana is \$0.054 per 1,000 cubic feet, which accounts for the leading position of that state in the production of carbon black. The manufacture of carbon black has been greatly restricted in many states in the interest of the conservation of natural gas.

Rare Compounds in Petroleum.—It has been proved that very rare organic compounds exist in petroleum. Little or no effort has been made to recover them, although research might show that these compounds were of tremendous value to man from a medicinal, a scientific, or an industrial standpoint. The great work of the late C. F. Mabery pointed to such possibilities, but little is being done in that direction now.

PRODUCTION OF OIL IN THE UNITED STATES

The United States is the leading producer of petroleum in the world. It was responsible for about 70 per cent of the world's output in 1928. The 1928 production was 900,000,000 barrels of oil, and 79,000,000 barrels was imported that year. The United States exported in 1928, however, 120,000,000 barrels of refined petroleum products and 18,000,000 barrels of crude oil.

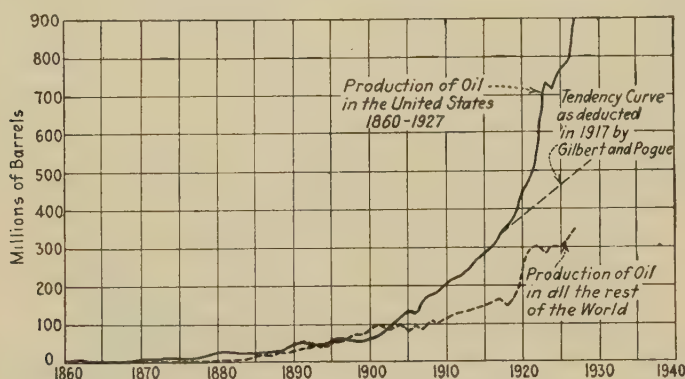


FIG. 189.—Curves showing the production of oil in the United States and the rest of the world from 1860 to 1927. (Data from U. S. Mineral Resources.)

The course of oil production from 1860 to 1928 is shown in Fig. 189, which also shows the position of the United States in world production. The tremendous increase in production after 1919 is notable. The straight broken line in the figure indicates the probable production as deduced by Gilbert and Pogue in 1917. The enormous increase in excess of the predicted production is in marked contrast with the similar prediction made for coal (see Fig. 148, p. 375). The great demand for internal-combustion motors (for automobiles, airplanes, and tractors) that use petroleum products is responsible for the increased production of oil.

The curve in Fig. 189 represents the actual oil production. Had the production been unchecked, however, the curve would have mounted much more rapidly. Unlimited output would have glutted the market, and therefore a curtailment policy has been adopted in most fields.

The production of petroleum in the United States comes from 19 states. Three states, namely, California, Oklahoma, and Texas, were

responsible for over 82 per cent of the total production of the United States in 1928, in fact, they yielded over 57 per cent of the world's production that year. The oil of these 19 states comes from more than 65 pools, that averaged, in 1928, 10,000 barrels each per day.

WORLD PRODUCTION OF PETROLEUM

Nearly all (95.8 per cent) of the world's production of petroleum comes from eight countries. These and their rank in world production in 1928 are as follows:

	Percentage of world's petroleum production, 1928
United States.....	69.7
Venezuela.....	8.2
Russia.....	6.2
Mexico.....	3.6
Persia.....	2.9
Rumania.....	2.1
Dutch East Indies.....	1.6
Colombia.....	1.5

The production of oil in the world in 1928 was over 1,000,000,000 barrels, yet the world's total output from 1857 to the end of 1928 was

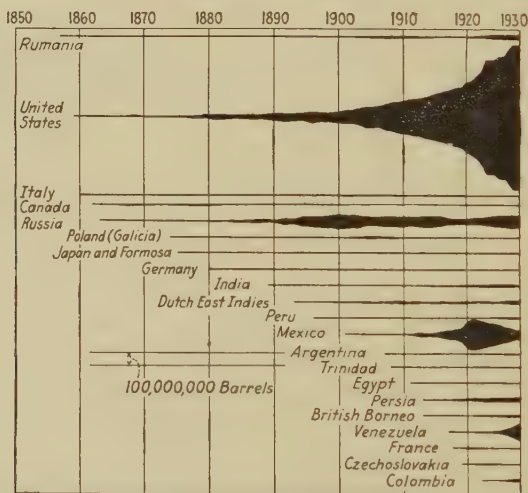


FIG. 190.—Graph showing the production of petroleum of all producing countries from date of initial production to 1928. (Data from U. S. Mineral Resources.)

only 17,110,000,000 barrels. The United States has produced 11,239,000,000 barrels of oil, or over 65 per cent of the total production. The position of the United States in oil production is well shown in Fig. 189. The date of initial production in each country and the total production by years is shown in Fig. 190 and also in Table 90.

The United States has never fallen below 41 per cent of the world's production, as Fig. 191 shows. In 1898, with development of the Baku field, the oil production of Russia surpassed that of the United States, but 4 years later the United States regained the lead. This increase of production was due to the discovery of oil in the Spindletop (Texas) pool. Other pools in Oklahoma, Texas, and California soon increased the output of the United States to 60 per cent or more of the world's total.

About the time of the decline in the Russian production came the discovery of oil in Mexico, a country which went rapidly to its peak in 1921 (see Fig. 186, p. 449). Venezuela, where oil was discovered in 1917, passed the million-barrel mark in 1921 and attained second place in world production in 1928.

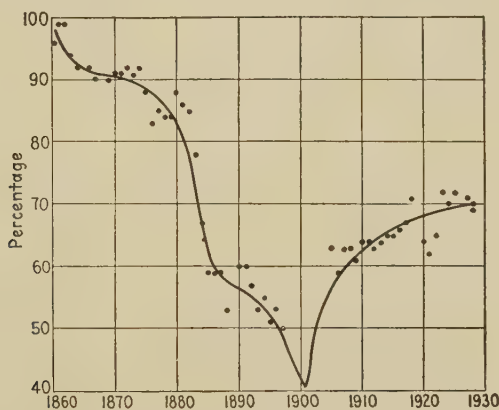


FIG. 191.—Curve showing the percentage of the world's total production of petroleum made by the United States from 1860 to 1928. The average is 62 per cent. (*Data from U. S. Mineral Resources.*)

The world-wide distribution of petroleum and of markets for the refined products have led the oil industry to look upon the production of petroleum as an international problem. Cutthroat competition and wasteful methods of production are being eliminated by cooperative efforts, which, in the end, can only mean economy and stabilization.

TABLE 90.—WORLD'S PRODUCTION OF CRUDE PETROLEUM, 1857-1928, BY YEARS AND COUNTRIES¹
(Thousands of barrels of 42 U. S. gallons)

Year	Roumania	United States	Italy	Canada	Russia	Poland (Galicia)	Japan and Taiwan	Germany	India	Dutch East Indies	Peru	Mexico	Argentina
1857-1860	19	502	2										
1861	17	2,114	2										
1862	23	3,057	2										
1863	28	2,611	2	12	41								
1864	33	2,116	2	83	65								
1865	39	2,498	2	90	67								
1866	42	3,598	1	175	83								
1867	51	3,347	1	190	120								
1868	56	3,646	2	200	88								
1869	59	4,215	2	220	202								
1870	84	5,261	2	250	204								
1871	90	5,205	2	270	165								
1872	91	6,293	2	308	185								
1873	104	9,894	2	365	475								
1874	103	10,927	1	169	583	150							
1875	180	8,788	1	220	697	158	5						
1876	111	9,133	3	312	1,321	164	7						
1877	108	13,350	3	312	1,801	170	10						
1878	109	15,397	4	312	2,401	176	18						
1879	110	19,914	3	575	2,761	215	23						
1880	115	26,286	2	350	3,001	229	26	9					
1881	122	27,661	1	275	3,601	287	17	29					
1882	136	30,350	2	275	4,538	330	15	58					
1883	139	23,450	2	250	6,002	365	20	27					
1884	211	24,218	3	250	10,805	408	28	46					
1885	193	21,859	2	250	13,925	465	30	41					
1886	168	28,065	2	584	18,006	306	38	74					
1887	182	28,283	1	526	18,368	344	29	74					
1888	210	27,612	1	695	23,049	467	37	85					
1889	298	35,164	1	705	24,609	515	53	68					
1890	383	46,824	3	795	28,691	659	52	108	94				
1891	488	54,293	8	755	34,573	631	53	109	118				
1892	593	50,515	18	780	35,775	646	69	101	190				
1893	535	48,431	19	798	40,457	693	106	100	242				
1894	508	49,344	21	829	36,375	949	173	123	299	600			
1895	576	52,892	26	726	46,140	1,453	170	121	327	688			
									372	1,216			

1896	543	60,960	18	727	47,221	2,444	237	145	430	1,427	47
1897	571	60,476	14	710	54,399	2,226	262	166	546	2,552	71
1898	776	55,364	15	758	61,610	2,376	319	184	542	2,964	71
1899	1,426	57,071	16	808	65,955	2,314	339	192	941	1,796	89
1900	1,629	63,621	12	913	75,780	2,347	371	358	1,079	2,253	274
1901	1,678	69,329	16	757	85,168	3,251	1,117	314	1,431	4,014	10
1902	2,060	88,767	19	531	80,540	4,142	996	354	1,617	2,430	257
1903	2,763	100,461	18	487	75,591	5,235	1,209	446	2,510	5,770	40
1904	3,599	117,081	26	553	78,537	5,947	1,219	637	3,385	6,508	290
1905	4,421	134,717	44	634	54,960	5,766	1,347	561	4,137	7,850	126
1906	6,378	126,494	54	569	58,897	5,468	1,564	579	4,016	8,181	251
1907	8,118	166,095	60	789	61,851	8,456	1,718	757	4,344	9,983	531
1908	8,252	178,527	51	528	62,187	12,612	1,871	1,009	5,047	10,283	751
1909	9,327	183,171	42	421	65,970	14,933	1,887	1,019	6,677	11,042	945
1910	9,724	209,557	51	316	70,337	12,673	1,829	1,032	6,138	11,031	1,411
1911	11,108	220,449	75	291	66,184	10,519	1,737	1,017	6,451	12,173	1,258
1912	12,076	222,935	54	243	68,019	8,535	1,659	1,031	7,117	10,846	1,465
1913	13,555	248,446	47	228	62,834	7,818	1,940	781	7,930	11,172	1,752
1914	12,827	263,763	40	215	67,020	6,436	2,636	703	8,202	11,422	2,071
1915	12,030	281,104	44	215	68,548	5,352	2,928	703	8,202	11,920	1,837
1916	8,945	300,767	51	198	65,817	6,587	2,963	656	8,491	12,547	2,579
1917	8,721	335,316	41	214	63,072	6,228	2,861	642	8,079	13,180	40
1918	8,730	355,928	35	305	27,168	6,032	2,311	270	8,188	12,778	50
1919	6,618	378,367	35	241	31,752	6,096	2,231	265	8,736	15,508	60
1920	7,435	442,929	35	196	25,430	5,607	2,221	246	8,375	17,529	70
1921	8,368	472,183	32	188	28,968	5,167	2,233	274	8,734	16,958	80
1922	9,843	557,531	31	179	35,692	5,227	2,055	319	8,529	17,066	90
1923	10,867	732,407	34	170	39,147	5,402	1,804	346	8,406	19,870	100
1924	13,369	713,940	45	161	45,355	5,657	1,814	406	8,416	20,473	110
1925	16,646	763,743	70	332	52,448	5,960	2,000	541	8,000	21,422	120
1926	23,292	770,874	..	365	62,941	5,844	1,557	653	8,270	20,817	130
1927	26,368	901,929	54	477	77,018	5,342	1,700	663	7,878	25,967	140
1928	28,000	896,000	55	600	80,000	5,600	1,700	720	8,000	21,500	150
Total.....	309,148	11,238,425	..	27,224	2,325,552	213,350	56,581	19,152	189,342	383,398	51,550

¹ U. S. Mineral Resources. ² Less than 1,000.

Selected Readings on Oil and Gas

There is a vast amount of literature on oil and gas, and the selections given here are only a few of the most important.

American Petroleum—"Supply and Demand," Am. Petroleum Inst., 1925.

BACON and HAMOR: "The American Petroleum Industry," McGraw-Hill Book Company, Inc., New York, 1916.

BOSWORTH, T. O.: "The Geology of the Mid-Continent Oil Fields," Macmillan Company, New York, 1920.

CLARKE, F. W.: The Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, pp. 731-755, 1924.

CUNNINGHAM-CRAIG, E. H.: "Oil Finding," London, 1920.

DAY, D. T.: "Handbook of Petroleum," John Wiley & Sons, Inc., New York, 1920.

EMMONS, W. H.: "Geology of Petroleum," McGraw-Hill Book Company, Inc., New York, 1921.

GARFIAS, V. R.: "Petroleum Resources of the World," John Wiley & Sons, Inc., New York, 1923.

GILBERT and POGUE: Petroleum, A Resource Interpretation, U. S. Nat. Museum *Bull.* 102, Part 6, 1918.

HAGER, DORSEY: "Practical Oil Geology," McGraw-Hill Book Company, Inc., New York, rev., 1926.

JOHNSON and HUNTLEY: "Oil and Gas Production," John Wiley & Sons, Inc., New York, 1916.

LEITH, C. K.: "Economic Aspects of Geology," pp. 128-153, Henry Holt and Company, New York, 1921.

LILLEY, E. R.: "The Geology of Petroleum and Natural Gas," D. Van Nostrand Company, Inc., New York, 1928.

PANYITY, L. S.: "Prospecting for Oil and Gas," John Wiley & Sons, Inc., New York, 1920.

RIES, H.: "Economic Geology," John Wiley & Sons, Inc., New York, 1925.

SPURR, J. E.: "Political and Commercial Geology," pp. 1-21, McGraw-Hill Book Company, Inc., New York, 1920.

STIGAND, I. A.: "Outlines of the Occurrence and Geology of Petroleum," 1925.

THOMPSON, A. B.: "Oil Field Development," 1916.

See *U. S. Mineral Resources and Mineral Industry* for data about production. They are issued each year. Especial attention should be called to the *Bulletin of American Association of Petroleum Geologists*, which contains a great deal of valuable material. *Economic Geology*, *American Institute Mining and Metallurgical Engineers Transactions*, bulletins of the U. S. Geological Survey, and the oil journals contain much information.

CHAPTER XIV

STRUCTURAL MATERIALS

INTRODUCTION

The next group of earth materials to be considered includes those products that enter into the innumerable types of structural and building operations. Some of these products, such as sand and gravel, are employed directly without any preparation; some, as the building stones, are merely dressed for use; and others must undergo considerable treatment to be prepared for their final use. The group includes, as one would expect, the simple building materials used by early man in his efforts toward constructing some type of shelter. They are stone, clay, and

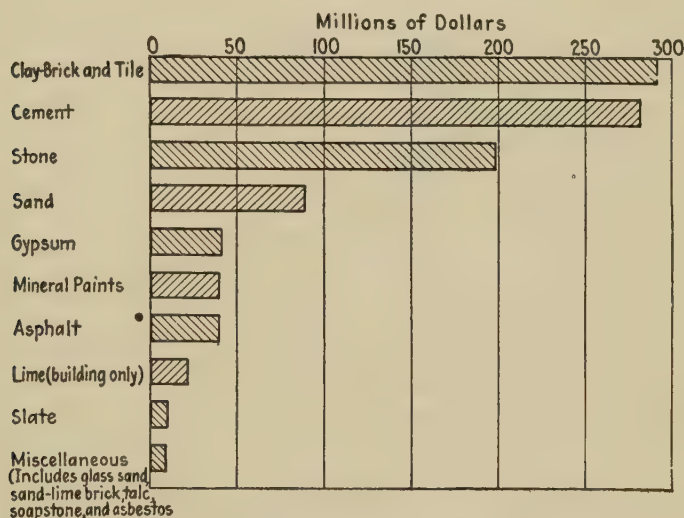


FIG. 192.—Value (estimated in some cases) of the materials used for structural purposes in the United States in 1927. (Data from U. S. Mineral Resources.)

sand. To these, others have been added the value of which depends upon the process of preparing them for use. Some of these prepared materials are lime, gypsum, and glass. Other materials than these non-metallic substances enter into the construction of a modern structure, but they are treated separately. The total value of the non-metallic materials used in structural work in the United States amounts to over a billion dollars annually.

The materials to be discussed in this chapter, in the order of their importance (Fig. 192), are as follows:

- Clay.
- Cement.
- Stone.
- Sand and gravel.
- Gypsum.
- Lime.
- Mineral paints (zinc and lead pigments, barite, and natural pigments).
- Asphalt.
- Asbestos.

Some of the materials in this list are not used exclusively in building operations, but the structural use is the dominant one for all. All of the uses of each product are given in this chapter. Some of the materials, such as lime and barite, have important applications in the chemical industries.

A striking fact that is impressed upon the traveler in Europe is the almost universal use of stone and brick (supplemented by concrete in recent years) in all types of buildings. A further interesting fact is the direct relationship between the building material and the general geology of the area. In the absence of a building stone near at hand, brick is used; for, although outcrops of a suitable stone may not be available, deposits of clay for making brick are almost always near at hand. Striking examples of the use of local building stone are to be found in Rome, where travertine has been employed extensively since the time of the early Romans; and in the north of Ireland on the lava flows, where the black basalt has been utilized. The use of a black stone is very unusual, and in order to brighten it and make the buildings more attractive, brick or a lighter-colored stone has been used around the windows and doors and on the corners of the buildings. On the Chalk Downs in England, the walls of churches and dwelling houses have often been constructed wholly of the flint nodules.

If there was a more extensive use of the earth materials for building in the United States, our enormous annual fire losses would be greatly reduced, to say nothing of the greatly increased life of our buildings.

CLAY AND CLAY PRODUCTS

The products manufactured from clay have many uses, as an examination of the list given in this chapter shows. In 1927, clay products ranked fourth in value among all the mineral products of the United States, comprising 7.46 per cent of the total value. Clay is easily molded into any shape desired and can be so readily treated with colors that it has long been a favorite material for both utilitarian and artistic purposes. Clay products are classed in two broad divisions: brick, tile, and terra

cotta; and pottery. There are other products, but these two groups contain the most important ones. The products of the first group are used dominantly for structural purposes. The original raw material employed in making all these products is some type of clay, but each product requires a clay with special properties or else a special treatment of the clay during manufacturing.

History.—As was stated in the second chapter in this book, clay was the second earth material used by ancient man. The student interested in the history of the development of industrial or artistic products will enjoy tracing the early story of clay, as it is one of the most fascinating of the histories of any of the earth materials. In addition to following the development of the uses of clay, the student will find much of the history of man depicted upon the products of each period, for on no other material is so perfect a record left. The wonderful clay wares of all types produced by different races during the last 3,000 years are all too inadequately described in the literature of the subject in spite of their abundance. Man, having early learned the adaptibility of clay to a wide variety of uses and having perfected his methods of manufacturing, next turned his attention to improving the beauty of his product. As a result, a wealth of artistic clay wares has been produced, especially during the 400 years from 1400 to 1800.

Definition of Clay.—Clay is a naturally occurring, finely divided mixture of silicates (mainly hydrous), oxides, carbonates, and usually more or less colloidal matter. Most clays are plastic when wet and after firing in a kiln become hard. Plasticity is the property that permits clay to be molded into any desired shape and is, therefore, an essential quality of all workable clays.

Physical Properties of Clay.—A knowledge of the physical and chemical properties of clay is essential in order to determine the use to which a clay can be put and the method of manufacture that must be used.

The following physical properties of a clay should be determined: *plasticity, tensile strength, shrinkage (air and fire), fusibility, and color after firing.*

Some clays have a high *plasticity* ("fat" clays) and others have a low plasticity ("lean" clays). Frequently, it is necessary to mix fat and lean clays to obtain the desired product. The plasticity must be adjusted to the process of manufacture.

The *tensile strength* of a clay indicates its ability to hold its shape after being molded and to withstand subsequent handling. The range in tensile strength is extremely wide: from 15 to 600 pounds per square inch.

Shrinkage is of two kinds: air and fire. The air shrinkage is caused by the loss of water during drying. Fire shrinkage takes place in the kiln and is greater than the air shrinkage. If the total of air and fire shrinkage is excessive (it should not exceed 10 per cent), the product will be warped.

Both air and fire shrinkage are variable and are maintained at the amount desired by mixing different clays.

The temperature at which a clay will melt or fuse (*fusibility*) is very important and must be determined. If that temperature is exceeded, the product softens and loses its shape and may even collapse. The process of melting passes through three stages: (1) *incipient fusion*, (2) *partial fusion*, and (3) *complete fusion*. To produce the vitrified brick used in paving, the second must be reached. Usually, the temperature at which the first and second stages take place is sufficiently different to insure proper control of the kiln temperature. A good fire clay should not fuse below 1,620°C.

The original *color* of a clay may or may not determine that of the final product. Red and yellow clays usually burn some shade of red, but if much lime is present, it reduces the red color to pink or buff. Black or gray shales may burn white (unless they contain too much iron) because the carbonaceous matter which gives the black or gray color burns off. If iron is present, some shade of red results. Many products, especially high-grade pottery, require pure, white-burning clays for their manufacture.

Chemical Composition.—The chemical composition of a clay is variable, but in the main a few oxides are dominant. These are *silica*, *alumina*, *iron oxides*, *lime*, *magnesia*, *the alkalis* (*potash* and *soda*), and *water*. *Sulfur*, *titanium oxide*, and *carbon dioxide* are minor constituents. The various properties of a clay depend upon the amounts of each of the constituent oxides.

Silica may be present as (1) sand grains, (2) silicates, and (3) colloids. Too much free quartz gives the clay an incipient fusion point that is too high and makes a lean clay. *Alumina* is a refractory compound, and too much of it makes a clay infusible. *Iron oxides* act chiefly as coloring agents but may also increase the fusibility of a clay. *Lime*, *magnesia*, and *the alkalis* increase the fusibility. *Water* and *carbon dioxide* are driven off in the kiln, as is also any *carbonaceous matter* in the clay. The carbonaceous matter is driven off at 800 to 900°C. Incipient fusion should not occur before the gases are eliminated, as the pores on the outside of the product would then be closed and the escape of the gases from the interior prevented. The gases would then expand and a porous or bloated product would be produced. If complete oxidation of any ferrous iron in the clay has not occurred before the fusion of the outer portion, the iron forms a blue-black interior known as "blue core."

ORIGIN AND MODE OF OCCURRENCE OF CLAYS

The origin of all the kinds of clay is essentially the same. They are usually the result of the breaking up, chemically, of some previously existing aluminous rock. The better types of clay are usually the result

of the breaking up of pegmatite dikes or of other rocks rich in feldspar. The chemical process that brings about these changes varies widely, depending as it does upon temperature and the composition of the solutions and of the original mineral. As a result of these varying conditions, clays of many kinds are formed. Kaolin is an important constituent of all clays, but various other claylike minerals are also present, sometimes in excess of the kaolin.

Residual clays are not always due to rock weathering but may be formed from the alteration of a rock by rising thermal solutions. The china-clay deposits near St. Austell, in Cornwall, England, were formed in this way.

Clays will be classified according to their mode of occurrence as *residual* and *transported clays* (Fig. 193).

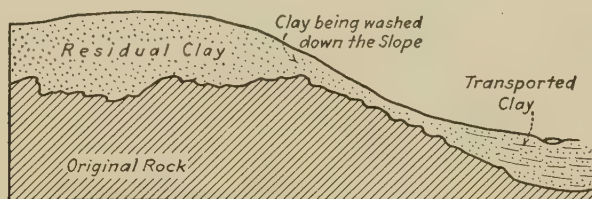


FIG. 193.—The relationship of residual clay to the original rock, and the origin of transported clays.

Residual Clays.—Residual clays, as the name implies, are clays that occur where they were formed. They have been produced by rock weathering and represent the insoluble material of the rock occurring immediately below them. They may have been derived from any aluminum-bearing mineral in a rock, whether it was present as an essential constituent, as the feldspars in an igneous rock, or as an impurity, such as kaolin in limestones and dolomites.

When a feldspathic rock, such as a granite or syenite, decays, the feldspar is broken up into kaolin (or a similar hydrous aluminum silicate), colloidal silica, and alkalis. The kaolin, the related clay minerals, and the colloidal silica make up the residual clay, which may also contain any other insoluble primary or secondary minerals. If there were iron-bearing minerals in the original rock, iron oxides would appear in the clay, unless an unusual amount of leaching had taken place. The impurities in a limestone are concentrated as a residual soil as the calcite goes into solution, but shales merely revert to clay, as they were originally composed of it. Indeed, many shales are quarried or mined and used in making brick or tile.

Residual clays may become very thick through long-continued decay of the underlying rock. Especially is this true where the surface slopes gently, as under this condition the weathered products are not readily

removed by running water. White residual clays are rare because rocks free from iron-bearing minerals are rare and because iron oxides as coloring agents are so common in all types of rocks. The white residual clays that do occur are usually of a very high grade.

Transported Clays.—Transported clays are those that have been shifted from their point of origin. They are more common than residual clays because the process of erosion is going on constantly and the weathered materials are being moved to lower levels.

The greater part of all clays has been deposited in water. Through consolidation, these clays may become shales. Where deposition has taken place in the ocean, the clays are known as *marine clays*. Deposition of the mud in estuaries or arms of the sea gives rise to *estuarian clays*. Where the accumulation is on the flood plains of rivers, the clays are called *flood-plain* or *alluvial* clays. Alluvial clay is an extremely common source of low-grade clays. Lakes may be filled up, forming *lake clays*. Clays deposited by ice are called *glacial clays*. These are common in the northern part of the United States. There are also other types of transported clays, of limited extent, which have been found suitable for special purposes. Each of these kinds of common clay has been found to be best adapted for some special product.

COMMERCIAL VARIETIES OF CLAY

Clay manufacturers recognize a great many different varieties and often name a clay merely from its use. A few of these varieties that are widely known are mentioned below.

Ball clay is any very plastic clay. *China clay* is a very pure kaolin clay that burns white and is used in making china or high-grade porcelain. *Flint clay* is a hard non-plastic clay and must be mixed with ball or other plastic clay before being used. *Refractory clay* is one containing a high percentage of aluminum, such as diaspore clay. *Paper clay* is used in giving body to and in surfacing paper. The uses of the following clays are evident from their names: *brick clay*, *pipe clay*, *earthenware clay*, *pottery clay*, *fire clay*, *retort clay*, *sewer-pipe clay*, *stoneware clay*, and *terra cotta clay*.

CLAY DEPOSITS OF THE UNITED STATES

Although many states contain a wide variety of clays within their borders, others have only the poorer kinds. Where a clay that is well suited for making a certain product is found in abundance, a large industry usually develops. This is especially true if the place is relatively near a market. Frequently, a cheap source of fuel, such as natural gas, is a deciding factor in the location of such an industry, or the plant may spring up at a point relatively near several different clays. Important

manufacturing centers for pottery in this country are East Liverpool, Ohio, and Trenton, New Jersey.

The Common Clays.—Clays for making brick, tile, sewer pipe, and other cheap clay products are found in nearly every state. Shales of all geologic ages (especially Tertiary and Pleistocene shales), marine clays, flood-plain clays, and glacial clays are all used for these purposes. If the common and vitrified brick made in the United States in 1925 were used for paving, they would make four highways, each 25 feet wide, extending from New York to San Francisco.

Kaolin or China Clay.—Special grades of clay are more limited in their distribution than common clays. Kaolin, the purest obtainable, was produced and sold in nine states in 1927 (some clay was undoubtedly produced and *used* by the manufacturer; but of this we have no record, so this and following deductions may not be entirely correct). The leading producing states were (in the order of their production) *Georgia, South Carolina, Pennsylvania, Florida, North Carolina, Maryland, Delaware, Vermont, and Nevada*. That our supplies of these high-grade clays are inadequate is shown by the fact that the United States imported that year 339,000 tons of kaolin or china clay. Much of the imported product came from Cornwall, England.

A china clay found in Georgia and South Carolina is a white-burning sedimentary clay of high grade and occurs in the Cretaceous formations. A similar type of plastic clay is found in the Tertiary formation of Florida.

Fire Clay.—Fire clay is of fairly wide distribution throughout the United States east of the Rockies. It occurs in beds of varying thicknesses and is found in rocks of many different ages. The most important deposits, however, are in the Carboniferous formations, especially those of the "coal measures." In these, the fire clay is in some places interbedded with the coal, although it does not necessarily underlie a coal bed, as is thought by some, for it often occurs unassociated with coal. About 32 states produced fire clay in varying amounts in 1927, but the major production of the year came from the following states (in the order of their production): *Pennsylvania, Missouri, Ohio, New Jersey, California, Colorado, Illinois, Indiana, and Alabama*. The fire clay constituted more than two-thirds of the total quantity of clay produced and sold in the United States that year. Again, much of the clay produced was used in the production plants and so was not represented in the figures as sold.

Pottery and Ball Clays.—Pottery clays include the best grades, though kaolins, of course, are the most important for producing high-grade porcelain. Ball clay is another important clay that is largely used in making high-grade pottery. *Kentucky, Tennessee, New Jersey, and Missouri* lead in its production. Much of it is imported, also.

Stoneware Clay.—Stoneware clays are closely related to fire clays and are found in the states that have deposits of fire clays.

Diaspore Clays.—Diaspore clays contain a varying amount of diaspore, $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, and are known as high-alumina clays. They are especially valuable for the manufacture of refractories. *Missouri* has large quantities of this valuable variety and is the only producer of it at present.

USES OF CLAYS

A complete list of the uses of clay would include the names of hundreds of products. There is hardly a phase of our daily life which does not make use of some clay product. Clay is used in the home as various forms of pottery and porcelain, as sanitary ware in the bathroom, as decorative materials, and as building materials in electrical apparatus. It is probable that as the price of copper goes up, we shall discard brass and bronze on doors and furniture and use various clay products that can, in part at least, replace them.

The following list is not exhaustive but illustrates the wide range of uses to which clay products are put:

TABLE 91.—PRODUCTS MADE FROM CLAY¹

Field of uses	Products in which clay is used in each field
Building operations.....	Common brick, vitrified brick, face brick, enameled brick, terra cotta, hollow building tile, conduits, silo and corn-crib tile, roofing tile, fireproofing tile, floor tile, ceramic mosaic tile, faience tile, wall tile, drain tile, sewer pipe, flue lining, wall coping, and chimney pots.
About the home.....	Porcelain china, Delft and Belleek ware, whiteware pottery, semiporcelain, red earthenware (enameled and glazed), stoneware, vitreous-china plumbing fixtures (lavatories, closet bowls, flush tanks, bath tubs, etc.), kitchen sinks, laundry tubs, red and brown white-lined cooking ware, majolica ware, door knobs, ornamental pottery and vases, statuary, porcelain stoves, and garden furniture.
Refractory wares.....	Various fire and vitrified brick, stove linings, high-alumina brick, chemical stoneware and porcelain (crucibles, retorts, assaying apparatus), and clay pots to use in glass melting.
Electrical wares.....	Electrical porcelain includes a long list of pieces: cleats, knobs, insulators, tubes, sockets, switches, plugs, conduits, etc.
Miscellaneous.....	Saggers, railroad ballast, septic tanks, grease traps, water conduits, and paving brick.

¹ Data, in part, from U. S. Bur. Census, 1926.

Clay has a long list of important applications in various manufacturing processes, in addition to its use in the clay products listed above. The following table is of interest in that it shows not only the uses of clay but also the kind and amount of clay employed in each use. It is surprising to learn that the amount of clay used as a paper filler and

surfacers is exceeded by that in only four other uses. Some other uses that should be noted are those in the manufacture of rubber, paints, cement, and fire-clay mortar. In addition to its employment as a filler in paper and rubber, clay is employed as a filler in linoleum, oilcloth, roofing, window shades, cotton goods, and ticking. A small amount is used in antiphlogistine. Pure white Portland cement is made from white clay.

TABLE 92.—USES OF CLAY SOLD BY PRODUCERS IN THE UNITED STATES, 1927

Use	Kaolin	Ball clay	Slip clay	Fire clay	Stone- ware clay	Miscel- lane- ous clay	Total
Short tons							
White-bodied ware made from white-burning clays.....	64,578	60,366		16,764	1,764		143,472
Art pottery.....	500	423		900	509	272	2,604
High-grade tile.....	22,790	29,905		18,639	568	3,814	75,716
Chemical stoneware.....	76			963	7,261	211	8,511
Stoneware.....		1,078		2,642	74,594		78,314
Enameling.....	26	708					734
Paper filler.....	192,307					1,201	193,508
Paper coating.....	3,510						3,510
Rubber.....	27,428			2,305		842	30,575
Oilcloth or linoleum.....	14,511						14,511
Paint filler or extender.....	12,084					1,250	13,334
Paint pigment.....	14	331					345
Architectural terra cotta.....	100	9,538		76,538	12,960	6,480	105,616
Asbestos products.....	440	579				1,364	2,383
Plaster and plaster products.....	6,224			11,491		4,075	21,790
Slip for glazing purposes.....			2,478				2,478
Cement.....	58,594			1,224			59,818
Kalsomine.....	3,959						3,959
Artificial abrasives.....		776	3,659	3,272	498	51	8,256
Crayons.....	500						500
Chemicals.....	1,500						1,500
Pencil leads.....						206	206
Saggers.....	5,304	15,238		144,210		300	165,052
Pins, stilts, and spurs for potters' use.....	300			6,346			6,646
Wads.....				33,463			33,463
Gas retorts.....				376			376
Fire brick and block.....	26,629			921,440		8,295	956,364
Fire-clay mortar.....	1,871	426		461,078			463,375
Bauxite and high-alumina brick.....				10,409		30	10,439
Glasshouse pots.....				25,184			25,184
Glasshouse supplies, blocks, tiles, etc.....	295	242		1,365			1,902
Zinc retorts and condensers.....				79,299			79,299
Clay crucibles.....				3,140			3,140
Graphite crucibles and stoppers.....		108					108
Foundries, steel works, etc.....	87			442,292	65	39,660	482,104
Unspecified ²	10,618	45		436,421	136	402,864	850,084
	454,245	119,763	6,137	2,699,761	98,355	470,915	3,849,176

¹ U. S. Mineral Resources, 1927, Part 2, p. 265.

² Includes clay for blast furnaces, building bricks, conduits, copper ladles, cosmetics, enameled brick, dobbies, filtering or decolorizing oil, flower pots, flue lining, hollow building tile, modeling, mortar colors, roofing tile, sewer pipe, smelters, soap, taxidermy, toy marbles, turpentine cups, water softener, etc.; also black-burning clay.

MANUFACTURE AND PRODUCTION OF CLAY PRODUCTS

Manufacture.—The manufacture of clay products involves an interesting series of steps, which due to lack of space cannot be described here in any detail. The following brief account is hardly more than an outline of the methods used, but even so it may prove of interest.

The clay (or shale) is dug from open pits or mined, then taken to the kiln and stored to allow it to soften or, more commonly, ground in what is known as a "dry pan." After passing through a screen, it goes to the mixer, where sufficient water is added to form a stiff mud. This mixing machine is called a "pugmill." From it, the clay goes to special machines that mold it into the desired forms: bricks, hollow tile, drain tile, sewer pipe, or any other. If some special surface is to be given the ware, it is done while the mud is soft. The product then passes through a drier or is dried in the sun or a large room and is ready for the kiln.

There are many types of kilns. The most common is the round beehive-shaped one. After the ware is placed in the kiln, the temperature is gradually raised to the point desired, and then the kiln is allowed to cool off. The heat is conducted upward or downward through it. Most common brick, such as hollow tile, drain tile, and some other wares, are brought just to the incipient fusion point. Vitrified wares, such as brick, sewer pipe, fire brick, and most pottery are heated to the point of partial fusion or vitrification.

Salt-glazed ware is made by rapidly raising the temperature and throwing salt on the fire. The elements in the salt, at the high temperature, cause the ware to fuse rapidly on the exterior, which gives the product a glazed surface. After cooling, the wares are sorted and are ready for market.

Certain of the products require more special treatment. Terra cotta has to be carefully molded, fired, and then any coloring or decorative designs added. The product is then dipped or sprayed with the glaze and placed in the kiln and fired again. The ware, after the first firing, is called "biscuitware," a name also applied to pottery and porcelain after their first firing. A *glaze* is transparent, so the color of the body of the ware or of any decorations put on it shows through it. An *enamel* is colored and is opaque so that the color of the body does not show through it. Most stoneware, garden pottery, and numerous other products are enameled, as are also some brick. Face brick undergo special treatment to give them some desired surface or color. A great many brick in lovely colors are being produced at present, and, as a result, more beautiful homes are being built.

Pottery of all kinds requires more care in its manufacture than the more common clay building products. More pains must be used in the

preparation of the clay; plastic clays, such as ball clay, being mixed with less plastic clays to get the desired plasticity, which is very important in pottery making. Frequently, clays have to be stored and allowed to "cure" for months or even a year. The molding requires the work of a skilled craftsman, as each piece must be made separately. After careful drying, the ware is given its first firing. This is not done in the open kiln where the flames or hot gases come in contact with the wares, but the ware is first placed in clay vessels, known as "saggers," which are closed by placing one on top of the other in the kiln.

A high degree of skill is required of the potter in decorating his ware. He may place raised figures on the biscuitware and then after firing dip or spray with a glaze and fire again. If colors are to be used, they are put on the biscuitware, fired to drive off the oil, taken out and glazed, and fired again. This process is underglaze decorating, and the result is very durable; but the number of colors that can be used under the glaze are limited to blue, brown, green, and yellow. The very delicately tinted porcelains have their decorations of pink and gold on the outside, although even pink and gold may be placed under the glaze if the temperature of the final firing is low and if it is not desired to keep the details of the design. Gold applied on the outside of the glaze wears off rapidly, as an examination of used gold-decorated china will disclose.

Lusterware is made by putting silver or copper in the glaze and firing at a low temperature in a specially constructed kiln. When the ware is just visibly red, smoke from wood (rosemary and gorse are widely used) is allowed to play on the ware long enough to produce a metallic film. The result is a product having a more or less iridescent luster.

The ceramic industry is an important one, and the ceramists have been making rapid strides in recent years in the production of clay wares. Many of the artistic efforts of the modern potter are comparable with the products of the period from the fifteenth to the eighteenth centuries, when the production of artistic clay wares was at its height. There is a growing public taste for the beautiful clay products of the artist.

Production.—The trend of the production of clay products in the United States is shown by Fig. 194. Since 1914, this has had a steady increase, and, at the same time, there has been a decrease in the number

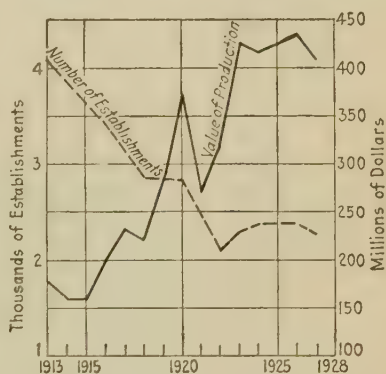


FIG. 194.—Curves showing value of the annual production of all clay wares in the United States from 1913 to 1927, and the decline in the number of plants producing clay products over the same period. (Data U. S. Bur. Census.)

of plants manufacturing such products (see Fig. 194). Figure 195 shows at a glance the relative value of the different types of clay products (not including pottery). Figure 196 shows the same facts for pottery production. Whiteware, which leads in amount, includes semiporcelain,

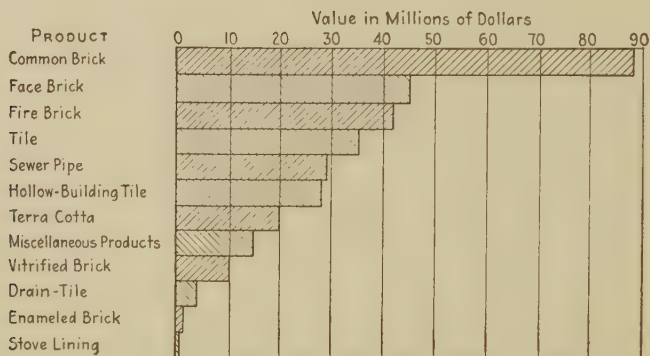


FIG. 195.—Graph showing the value of the various clay products (not including pottery) in the United States in 1926. (Data from U. S. Bur. Census.)

semivitreous porcelain, white granite, and cream-colored wares. The importance of clay plumbing fixtures is shown by the production figures for vitreous-china plumbing fixtures and semivitreous plumbing fixtures.

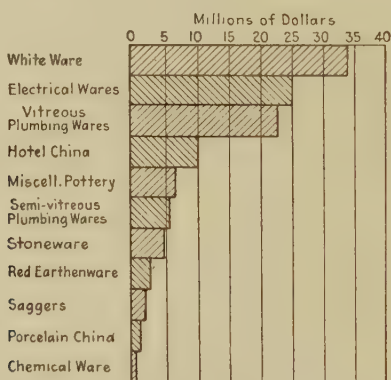


FIG. 196.—Value of pottery production in United States (in 1926) by classes of ware. (Data from U. S. Bur. Census.)

Selected Readings on Clay

- MERRILL, G. P.: "Rocks, Rock-weathering, and Soils," The Macmillan Company, New York, 1904
- RIES, H.: "Clays: Occurrence, Properties, and Uses," John Wiley & Sons, Inc., New York, 1908. The best book on the subject.
- : "Economic Geology," pp. 170-186, John Wiley & Sons, Inc., New York, 1925.

—and LEIGHTON: "A History of the Clay-working Industry in the United States," John Wiley & Sons, Inc., New York.

SEARLE, A. B.: "Chemical and Physical Properties of Clays and Other Ceramic Materials," His Majesty's Stationery Office, London, 1924.

WHEELER, H. A.: Mo. Geol. Survey, vol. XI, 1896.

WILSON: "Ceramics—Clay Technology," McGraw-Hill Book Company, Inc., New York, 1927.

There are numerous state reports on clays, and the U. S. Geological Survey and Bureau of Mines have valuable publications on the subject. Further information can be secured from the *Transactions* and *Journal* of the American Ceramic Society.

CEMENT

Man has long used some sort of material as a binder or mortar for building purposes. At first, wet clay was so employed, but later other materials were substituted, and we find the Egyptians using plaster as long ago as 5000 B.C. A material which would prevent the passage of



FIG. 197.—The Pantheon in Rome (built A. D. 123, during Hadrian's reign) is one of the finest examples of the early use of cement. (Photograph by W. A. Tarr.)

water, however, or which would harden in water was needed; and there is little doubt but that many attempts were made to produce such a material.

Early History of Cement.—Just what people first produced and used a natural cement is unknown. The Romans were great builders, as the ruins of the Empire testify. They were familiar with cement and used it in a great many of their structures. The Pantheon, built during Hadrian's reign, is probably one of the finest examples of the early use of cement in existence today (see Fig. 197). Yet the Romans were

evidently not the first to use this material, for the people of Carthage employed it in building a 70-mile aqueduct in northern Africa long before the Roman Empire was established. The Romans may have learned of cement from them. We do know that the Romans made a cement by mixing unslaked lime and volcanic ash. The product of this mixture not only could form a firm, hard cement, but it also possessed the property of hardening in water. It became known as "Pozzuolian cement" from the small town of Pozzuoli near Naples where it was made. Although it was long used by the Romans, the secret of making it apparently became lost during the Middle Ages, for only lime mortars were used then.

Cement Making Rediscovered in England.—The process of making natural cement was rediscovered by John Smeaton, an English contractor, in 1756. Smeaton's discovery evidently arose from his need of a cement which would be better than mortar, for he had the contract to build a lighthouse on the Eddystone rocks in the English Channel. Little is known of the use that was made of Smeaton's discovery, and 40 years later (1796) Parker, another Englishman, took out a patent for a natural cement which rapidly came into general use.

Early History of Cement in the United States.—In America, a rock suitable for making natural cement was discovered during the building of the Erie Canal, 1818 to 1819. This was a very timely discovery, for a cement having hydraulic properties was needed in the construction of the locks. Other localities were soon discovered where materials suitable for the manufacture of cement occurred, and the production of natural cements led in the United States until 1900, when that of Portland cement exceeded it. Since then, the output of natural cement has rapidly declined.

Invention of Portland Cement.—Portland cement was invented by Joseph Aspdin of Leeds, England, in 1824. Instead of using a natural mixture of the materials in cement, he mixed them in definite proportions. He called his product "Portland" cement because it resembled in color the famous Portland stone so extensively quarried on the Isle of Portland in the south of England. Although it was superior to natural cement, its manufacture was more difficult to control; and, as a result, its use spread slowly over Europe and finally reached the United States in 1872. It was first made in this country near Coplay, Pennsylvania. The annual production did not reach the million-barrel mark in the United States until 1896.

Later History of Cement in the United States.—The production of cement grew slowly in the United States after its first manufacture, and the total annual production never exceeded 10,000,000 barrels until 1897. After this time, it mounted rapidly until the value of cement in 1928 was sixth among the mineral products.

The uses to which this material has been put in recent years are so varied and important that the demand for it has become enormous. Its strength, ease of handling, and adaptibility to any form of construction work are the factors creating this demand. It should be noted that cement, which was developed for use in water and formerly called "hydraulic" cement because of this, is now used in all types of building and engineering work, not 10 per cent being employed for purely hydraulic purposes (see Table 94, p. 483).

Definition of Cement.—Cement is a prepared material that sets or becomes hard after it has been mixed with water. If mixed with gravel, sand, crushed stone, or ashes, it is called "concrete." A hydraulic cement is one that will set under water. All three of the cements described later will do this. The formation of certain compounds from the union of lime with silica, alumina, or iron during the manufacture of the cement gives it this property of becoming hard. There are three classes of cement: (1) Portland, (2) natural, and (3) Pozzuolian; but only the first one is of importance now.

Materials Used in Portland Cement.—Limestone mixed with clay or shale is the most common aggregate used in manufacturing Portland cement. This mixture constitutes more than half of the raw materials used. An ideal rock for making cement would be a limestone containing 20 to 25 per cent clay. Such a rock is called "cement rock," but this ideal combination is never found. The nearest approach to it is a rock found in the Lehigh Valley, Pennsylvania; but, even to this, pure limestone must be added to obtain the proper mixture. In recent years, blast-furnace slag mixed with limestone has been used increasingly, and this slag now makes up about 10 per cent of the materials used. Portland cement constitutes nearly 99 per cent of the cement production of the United States.

Manufacture of Portland Cement.—Portland cement is made by burning (actually fusing) a finely ground mixture of definite proportions of (1) limestone and clay (61.8 per cent in 1926); (2) marl and clay (2 per cent); (3) blast-furnace slag and limestone (9.4 per cent); (4) cement rock and limestone (26.8 per cent); and (5) oyster shells and clay [percentage included with (1)]. The chemical proportions are usually about 75 per cent calcium carbonate and 25 per cent clay materials (aluminum silicates) and iron oxides. This mixture is placed in a rotating kiln (Fig. 198) from 100 to 240 feet in length and heated to a temperature of 1,370 to 1,650°C. The raw materials are fused to a hard, glassy clinker. Figure 199 shows diagrammatically the successive steps in making cement. In making one barrel (376 pounds) of cement, 628 pounds of raw materials and about 200 pounds of finely powdered coal are used. The following table shows the amounts of each material that went into the Portland cement production of the United States in 1926:

TABLE 93.—AMOUNT OF RAW MATERIALS USED IN PORTLAND CEMENT IN THE UNITED STATES, 1926¹

Material	Quantity, short tons
Limestone and cement rock.....	41,583,000
Clay and shale.....	5,160,000
Blast-furnace slag.....	1,546,000
Marl.....	1,276,000
Gypsum.....	1,042,000
Oyster shells, sand, ashes, and caustic waste.....	1,010,000
Total.....	51,617,000

¹ U. S. Mineral Resources, 1926, Part 2, p. 326.

During the fusion of the cement materials, the lime combines with the silica, alumina, and iron to form various compounds: calcium silicates

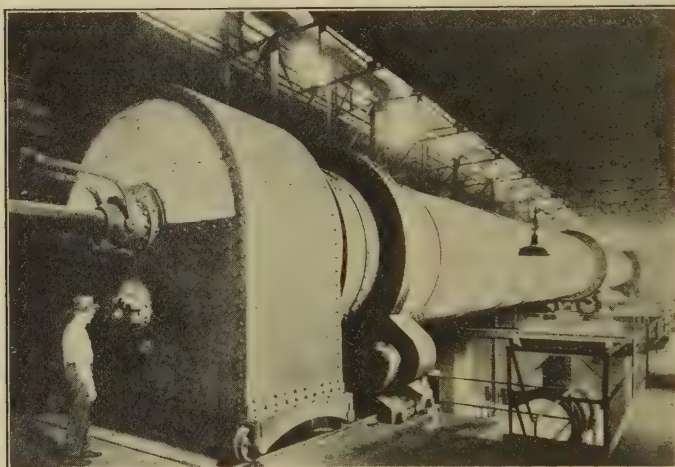


FIG. 198.—Modern rotary kiln used in the manufacture of Portland cement. Powdered coal is used for fuel in the kilns. It is blown in through a pipe (above the man's head in the picture). It burns with a tongue of flame 30 feet long and develops a temperature of 1,370 to 1,650°C. (2,500 to 3,000°F.). (Photograph furnished by the Portland Cement Association.)

calcium aluminates, and calcium ferrates. The clinker is then ground extremely fine; 78 per cent of it must pass through a screen with 40,000 openings per square inch, *i.e.*, a 200-mesh sieve. A retarder (usually raw gypsum in amounts not to exceed 3 per cent) is then added to prevent its setting too rapidly. When water is added to the cement, it combines with the fused products to form complex hydrous compounds of calcium, iron, aluminum, and silica. Some of these substances are crystals, and others are hard, amorphous substances. It is the development of these crystals (that interlock) and the hard amorphous substances that causes the cement to set and gives it great strength. All these substances require much water for their formation; hence, cement must be kept wet to set

fully. Using it under water, therefore, aids in giving it its full strength. The setting of the cement after it has been mixed with sand and gravel or broken rock binds all together in a rocklike mass which has great strength. The following diagrams show the average composition of the

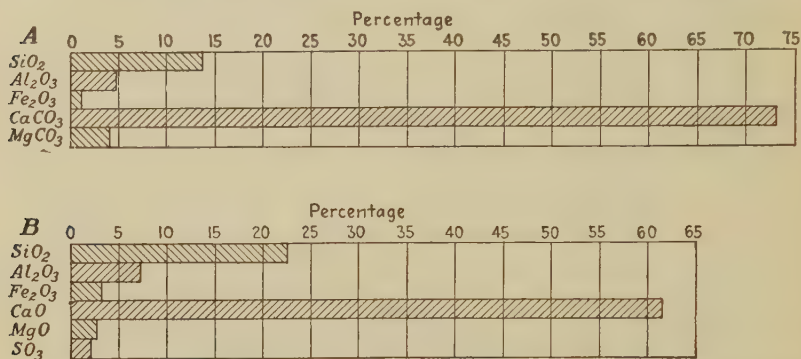


FIG. 200.—Graph showing the composition of an average Portland-cement mixture before firing, and of average Portland cement. A, average composition of four cement mixtures. (U. S. Geol. Survey.) B, average composition of three Portland cements. (Ries; "Economic Geology," p. 193, 1925.)

raw Portland cement mixture and of the final burned product or Portland cement (Fig. 200).

Natural Cement.—Natural cement is manufactured by burning a naturally impure limestone, containing from 15 to 40 per cent of clayey

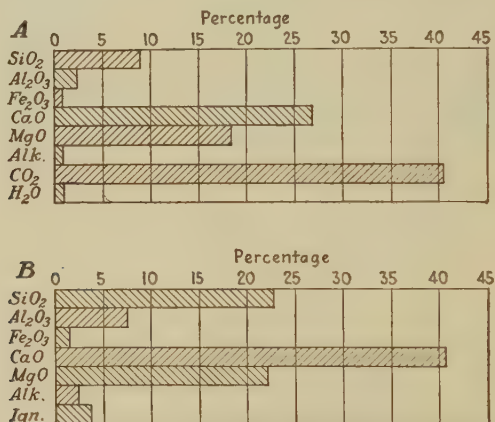


FIG. 201.—Graph showing the composition of the original natural cement rock and the resulting natural rock cement. A, composition of natural cement rock, before burning, from Akron, Ohio. B, composition of the cement, after burning. (Ries; "Economic Geology," pp. 190-191, 1925.)

material, at a temperature just below clinkering. This burning can be done in an ordinary lime kiln. The process involves driving off the moisture and carbon dioxide and combining the lime and magnesia with

the clayey materials to form silicates and aluminates. Natural cements set rapidly but are not so strong as Portland cement. As would be expected, their composition is variable. They may contain 20 per cent or more MgO, which, in Portland cement, is usually less than 5 per cent. (Compare Figs. 201 *B* and 200 *B* for the differences in the two cements.)

Previous to 1897, the production of natural cement exceeded that of Portland cement in the United States, but since then its production has fallen continually until at present (1929) it is insignificant.

Pozzuolian Cement.—Pozzuolian cement is a mixture of unslaked lime and volcanic ash or (as made today) furnace slag. It is somewhat similar to natural cement in its properties but is lower in grade. The production has fallen off greatly in recent years and is now relatively unimportant.

Distribution of Cement Materials in the United States.—There are few states which do not possess limestone, marble, or marl and clay or shale in sufficiently close association to permit of the manufacture of cement. Cement plants are located where such favorable associations of materials occur. The accompanying map shows the location of the cement plants in 29 states (Fig. 202).

Age of Rocks Used in Making Cement.—Rocks suitable for making cement are of all geological ages. Throughout the Appalachian region, the Paleozoic rocks are used abundantly, especially in the Lehigh Valley, which produces about 25 per cent of the entire production of cement in the United States. In Michigan and northern Indiana, marl and the associated Pleistocene clays are favorite materials. Those plants west of the Mississippi River use materials of any age.

Uses of Cement.—The use of cement has increased tremendously in the last 25 years (see Fig. 203). The following table gives the estimated consumption of Portland cement in the United States in 1926 by uses. It shows that 80 per cent goes into buildings, small-town and farm uses, and the paving of streets and highways. Entire structures are now being

TABLE 94.—ESTIMATED CONSUMPTION, BY USES, OF PORTLAND CEMENT IN THE UNITED STATES

Use	Percentage
Public and commercial buildings.....	26.0
Houses (exclusive of rural).....	8.5
Sidewalks and private driveways (exclusive of rural).....	5.5
Small town and farm uses.....	18.0
Sewerage, drainage, irrigation, culverts, concrete pipe.....	4.5
Paving and highways.....	27.5
Railways.....	5.5
Bridges, river and harbor work, dams and water-power projects, storage tanks and reservoirs.....	3.0
Miscellaneous.....	1.5
Total.....	100.0

¹ U. S. Mineral Resources, 1926, Part 2, p. 319; data from *Concrete*, May, 1926.

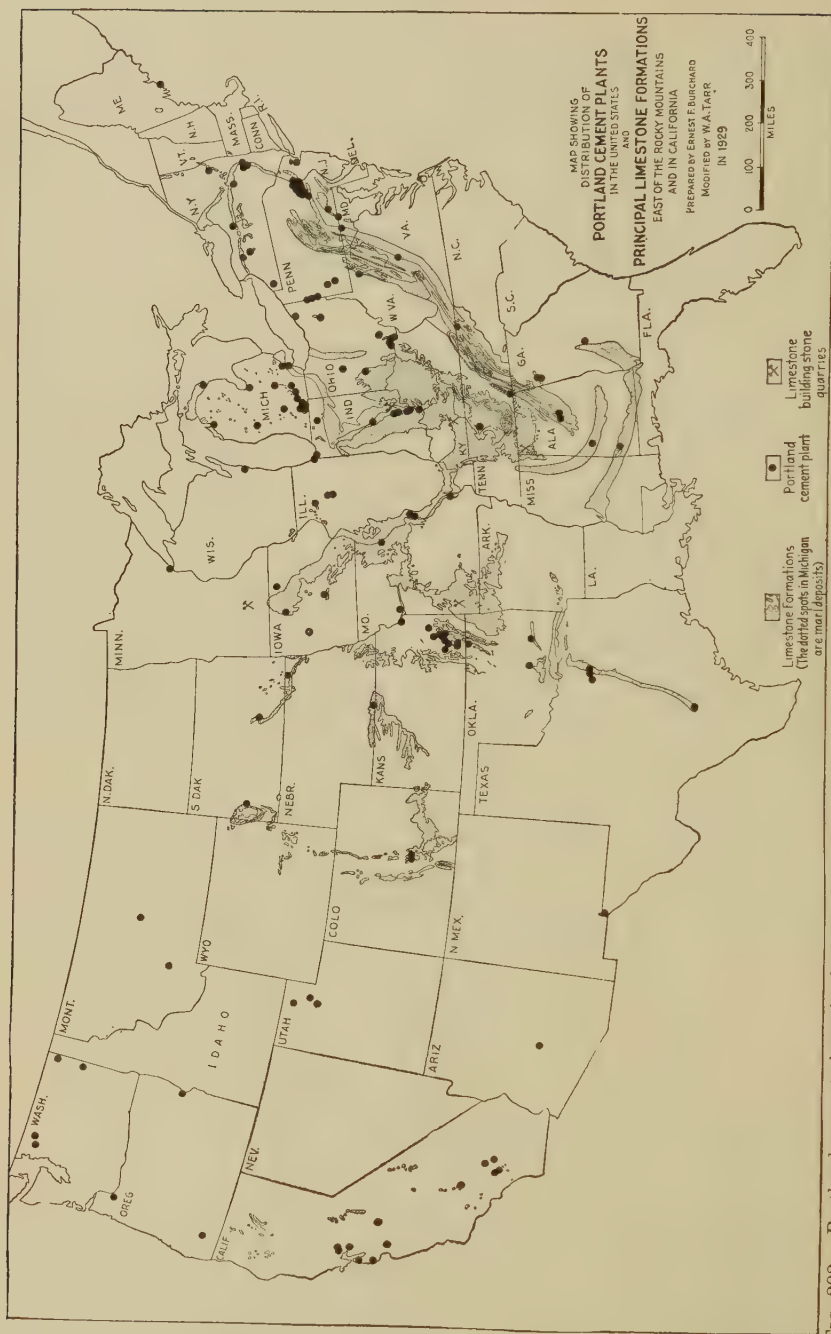


FIG. 202.—Portland cement plants in the United States and the principal limestone formations east of the Rocky Mountains. (Modified after Burchard, U. S. Mineral Resources.)

made of cement (concrete), though formerly only the foundations were made of it. Considerable cement goes into plaster, also, but the amount of Portland cement used in concrete exceeds that in any other use. Reinforced concrete has been found to be more resistant to earthquake shocks and fire than any other form of structural material, and with its development the uses of cement have been greatly extended.

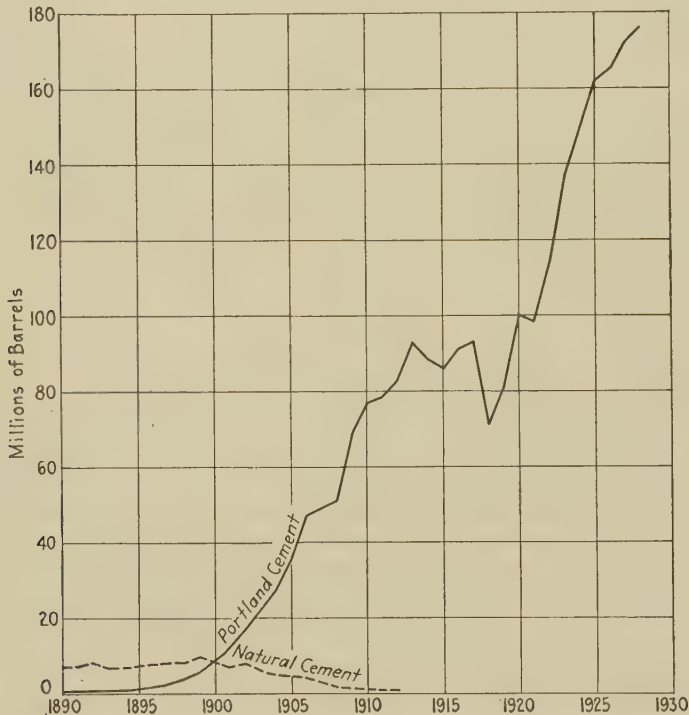


FIG. 203.—Curve showing the production of Portland cement from 1890 to 1928, and the production of natural cement up to 1912. (*U. S. Mineral Resources.*)

A very extensive use of cement in the United States is on highways, streets, and sidewalks. Its use for these purposes is rapidly growing. According to *American Highways*, on Jan. 1, 1928, there was completed and under construction 38,000 miles of concrete highways. The upward trend of the production curve of cement after the war period is undoubtedly largely due to the tremendous road-building program throughout the country. Twenty-five million automobiles create a demand for a high-class paving, and Portland cement paving fully meets this requirement. As Portland cement sets as well under water as out, it is extensively used in the construction of bridges, harbors, and sea walls. In order to meet certain particular purposes, various special cements have been produced.

Especially notable among them are quick-setting and quick-hardening cements, some of which attain their full strength in a few days or even in a few hours.

Selected Readings on Cement

- BLEININGER, A. V.: Manufacture of Hydraulic Cements, Ohio Geol. Survey *Bull.* 3, 4th ser., 1904.
- LINES, and LAYMAN: Portland Cement Resources of Illinois, Ill. Geol. Survey *Bull.* 17, 1912.
- ECKEL, E. C.: "Cements, Limes, and Plasters," John Wiley & Sons, Inc., New York, 1922.
- : Portland Cement Materials and Industry of the United States, U. S. Geol. Survey *Bull.* 522, 1913.
- ENO, F. H.: Uses of Hydraulic Materials, Ohio Geol. Survey *Bull.* 2, 4th ser., 1904.
- PECK, F. B.: The Lehigh Cement District, *Econ. Geol.*, vol. III, p. 37, 1908.
- RIES, H.: Lime and Cement Industries of New York, N. Y. State Mus. *Bull.* 44, pp. 640-648, 1903.
- Use of Concrete on the Farm, U. S. Dept. Agr., Office of Public Roads, Farmers' *Bull.* 461, 1911.

STONE

The nomadic ancestors of modern man had little use for permanency in their shelters and, therefore, left no traces of their efforts at building. When they had settled down, however, they undoubtedly began to build more or less permanent shelters. In hot and warm climates, these shelters were built of less durable materials than those in the colder regions. The earliest inhabitants of the cold regions occupied caves, but eventually they began to build; of stone, where it was available; and of sun-dried bricks, where it was not. Sir Flinders Petrie, the great English Egyptologist, has found horizons in the valley of the Nile which he dates at 14000 B.C. In them, much burned pottery occurs; hence, we may assume that the people of that time could also make brick. No doubt, the use of stone long antedated this period, going back to the neolithic age; although there is no evidence that either the Aurignacians or the Magdalenians built stone houses. Their skill in making stone implements, however, favors the view that they were able to build in stone.

Early History of Stone.—There is little doubt but that man has utilized stone in building shelters for the last 8,000 or 10,000 years. The ruins of splendid buildings in Europe, Asia, and northern Africa as well as those of a later period in South America (buildings of the Incas) and in Central America (Maya dwellings) all testify to this view.

The mortised joints in the stonework of the Incas in Peru are an outstanding achievement in stone construction work. These joints fit accurately and were made on blocks some of which were 12 feet in length. The Incas moved stones, 36 feet long, over 20 miles. One of these stones contained 1,246 cubic feet and weighed about 93 tons.

The wonderful structures in Europe are evidence of man's artistic, as well as extensive, use of stone. When one gazes upon Rheims Cathedral or the red sandstone cathedral in Freiburg, Baden, Germany, or the beautiful fan vaulting in King's College Chapel at Cambridge University, England, or the Milan Cathedral, he may well wish that we were still using stone; for these products of the stone artisan are among man's most beautiful achievements.

Early History of Stone in the United States.—Stone has been used for building purposes in the United States since the first settlements were made, though not so extensively as in the home countries of the settlers. These early settlers used timber more extensively for building, probably because of its great abundance and on account of the greater ease with which it is worked up. That stone was not commonly used is shown by the scarcity of buildings dating back to the seventeenth and eighteenth centuries. Stone was very accessible throughout New England. Some granite was used in this early period, but sandstone seems to have been the favorite stone. The granite was quarried at Quincy, Massachusetts. Slate was widely used during the seventeenth and eighteenth centuries for tombstones, door steps, and monuments, marble coming into use during the nineteenth century for the same purposes. The first marble-faced building was not erected until 1854. The great development of the building-stone industry began about this time, when the extension of the railroads had made possible the opening and development of quarries in Massachusetts, Vermont, New York, and other previously inaccessible places.

Later History of Stone in the United States.—After the Civil War, the use of stone gradually increased, until in the eighties, when it began to increase rapidly. About this time, the oolitic limestone of Bedford, Indiana, was introduced throughout the United States east of the Roicky Mountains and rapidly replaced the darker stones of the earlier period. During the last 20 years, the great increase in the use of cement and clay products in building has been a factor in restricting the use of building stone. A great amount of stone is used, however, as crushed stone in concrete. Much stone is now employed in thin slabs to cover the steel skeletons of the modern building structures. Its increasing use by various industries that require it in some phase of their manufacturing processes aids in keeping its production about constant.

Reasons for Use of Stone.—Strength, durability, and great adaptability to use are the qualities that make stone so very desirable as a building material. The beauty of many building stones is also an important factor in determining their choice. The initial cost of a stone is probably regarded as the most important factor governing its use, but this should never be given first consideration. The fact of the

long life of stone should entirely overshadow the consideration of initial cost.

Fashion is a factor that is allowed to dictate the choice of building materials, and it often causes the selection of a stone unsuited for the use to which it is put. The famous brownstone of Connecticut and New Jersey (very fashionable during the period of 1850 to 1885) and the Bedford limestone of Indiana, very extensively used at present, are stones that are easily prepared for market and have a wide adaptability but are, however, not suited for every purpose or for all types of structures. The brownstone was used so extensively in New York City in the eighties that the effect along many streets was monotonous.

Factors Governing the Price of Stone.—The cost of quarrying, preparation for the market, and length of haul are factors that influence the price of a stone. This price may be so low as to be the deciding factor in favor of its use, the element of durability being disregarded. If a stone is to be used for furnace flux, crushed stone, and similar purposes, where the haul is usually short, the cost of quarrying is the principal element in determining price.

Physical Properties of Building Stone.—Several essential properties of a building stone should be considered before deciding upon its use for a specific purpose. These are (1) *strength*, (2) *color*, (3) *texture*, (4) *resistance to water, frost, and heat*, and (6) *durability*.

Strength.—Practically any stone that can be quarried, dressed, and handled has sufficient strength for most building purposes. Soft rocks are never employed in building operations. The tuffs of the southwestern states are among the softest rocks used anywhere for building. They become somewhat harder upon exposure and anyway are well suited for use in the dry climate of that region. A tuffaceous rock was used by the Romans and has withstood weathering remarkably well.

The strength of building stones (as determined by crushing square blocks, 2 by 2 by 2 inches) ranges from 3,000 or 4,000 pounds per square inch to 30,000 or 40,000 pounds per square inch. A stone having a crushing strength of 2,000 pounds per square inch and weighing 150 pounds per cubic foot would support a column of rock nearly 2,000 feet high. The builder usually employs a factor of safety, *i.e.*, he figures the actual weight which the lowest course of stone in a building will have to support and then multiplies this weight by 10, 15, or 20. He then uses a stone that will support this increased weight. Taking the Washington Monument as an example, the maximum pressure at the base of it is 314.6 pounds per square inch, and allowing a factor of safety of 20, the pressure would be 6,292 pounds per square inch. The actual strength of the stone in the monument is from 10,000 to 12,000 pounds per square inch, or about double the strength required, even with a factor of safety of 20.

The following table shows the strength of some common rocks:

TABLE 95.—CRUSHING STRENGTH OF SOME COMMON ROCKS

Kind of rock	Locality	Strength, pounds per square inch
Granite.....	{ Graniteville, Mo.	28,530
	{ Knoblick, Mo. (average of two tests)	34,875
	{ Berlin, Wis.	24,800
	{ Millbridge, Me.	19,917
Limestone.....	{ Bedford, Ind.	4,800
	{ Bedford, Ind.	6,500
	{ Cobbleskill, N. Y.	21,066
	{ Carthage, Mo.	12,684
Marble.....	Rutland, Vt.	13,864
Sandstone.....	{ Little Falls, N. J.	9,500
	{ Cleveland, Ohio	6,800

Color.—Building stones have a wide range of colors; but those most commonly used are white, gray, brown, green, red, pink, and, more rarely, black. The color of a rock depends upon that of its mineral constituents or upon some impurity acting as a coloring agent. The gray in granites is due to a mixture of biotite or hornblende and white feldspar and quartz. Green is commonly due to the presence of chlorite in a rock. Red and pink colors, whether in igneous or sedimentary rocks, are due to varying amounts of hematite. Browns are the result of mixtures of the iron oxides. Black and grays in sedimentary rocks and in slates are due to the presence of carbonaceous materials. Variegated marble or onyx is due to the color's being deposited in layers. Most colors are permanent, but a few may change. For instance, blacks and grays, due to carbonaceous matter, may fade; and yellow may change to brown through the dehydration of iron oxide. Pyrite may oxidize to limonite or hematite, which stains the rock in an unsightly manner.

Texture.—In general, a fine-textured rock is stronger and more resistant than one of course texture. A fine-textured rock splits more easily and dresses more smoothly than a coarse-textured one, and therefore texture influences the cost of a stone.

Resistance to Water, Frost, and Heat.—All rocks are more or less porous and so can absorb some water. Granites have less than 0.5 per cent pore space; marbles the same; limestone from 0.55 to 13.38 per cent; and sandstone from 5 to 25 per cent. If the porosity of a stone is too high, water may find its way entirely through a wall, or even if this does not occur, the wall will be damp and the life of the stone greatly shortened. Most igneous and metamorphic rocks and limestones are dense and so have little pore space.

Frost action is not serious unless the rock is porous and contains water. The water, on freezing, increases its volume about one-tenth, and the expansion disrupts the rock. The results of frost action are frequently seen in the scaling off of thin layers from the surface of sandstones or even limestones, especially where the stone has been incorrectly placed on edge in the wall.

Heat, if sufficiently high, will destroy any rock. Experiments by Tarr¹ have shown that granite was ruined at 500°C. The disruption is due to the irregular expansion of the minerals composing the granite or other rock. Marble and limestone are easily ruined under similar conditions.

The amount of expansion and contraction due to daily changes in temperature (aided, no doubt, by moisture) is sufficient to cause a rock to scale off after years of exposure. The surface of a building becomes highly heated during the day and expands. As rock conducts heat slowly, this expansion is mainly at the surface. When night comes, the temperature drops rapidly and the highly heated surfaces lose heat and contract. This sets up strains within the rock which are relieved after a time by cracking, and a thin shell splits off of the face of the rock. Old buildings may thus become very unsightly, and the condition can be remedied only by going over the building with a hammer to resurface the stone. Some of the college buildings at Oxford University, England, are in very bad condition in this way and are now in process of being renewed.

Durability.—The durability of a stone is its ability to withstand the effects of *weathering* and *use*.

Weathering effects include the action of temperature changes; the action of water and its contained acids; and the gases, such as carbon dioxide and sulfur dioxide, in the atmosphere. Few people realize how much acid is contained in the rainfall of our cities as a result of the burning of coal containing sulfur. The temperature changes are mechanical changes; those produced by water and its acid content are chemical changes. The result of weathering is shown in the roughened surfaces of polished stones. The water and its acids attack the surface and remove some of the rock in solution; the heat and frost chip off small fragments; and finally the rock crumbles.

The length of life of various building stones under the climatic conditions of New York is shown in Table 96.

Julien does not give figures for slate, which is very durable. A study by the author of this book of slate monuments indicated a life of 200 years for slate before marked decay began. Julien's figures for granite are far too low (unless the climate is extremely variable) and should be more than

¹Tarr, W. A., A Study of the Effects of Heat on Missouri Granites, Univ. of Mo. Bull., vol. 15, No. 27, 1914.

TABLE 96.—LIFE OF VARIOUS BUILDING STONES IN NEW YORK CLIMATE¹

Kind of stone	Life, years
Coarse brownstone.....	5 to 15
Fine laminated brownstone.....	20 to 50
Compact brownstone.....	100 to 200
Coarse fossiliferous limestone.....	20 to 40
Fine oolitic limestone (French).....	30 to 40
Coarse dolomitic marble.....	40
Fine dolomitic marble.....	60 to 80
Fine marble.....	50 to 100
Granite.....	50 to 200

¹ Taken from studies of A. A. Julien.

doubled. In most parts of the United States, very few marbles or limestones retain a polish for 50 years.

A porous limestone, such as the Portland stone of England, used so extensively 300 years ago by Sir Christopher Wren in the construction of his churches, disintegrates rather rapidly in cities under moist conditions. Many figures made of this stone, having spent 300 years in the London climate, are now unrecognizable.

How climate affects the life of a stone is shown also by the condition of the Egyptian obelisk in New York City. This obelisk, of the time of Thothmes III (about 1500 B.C.), was moved to Central Park in 1881. Although it had remained perfect in the Egyptian climate for 3,300 years (even retaining its polish), it began to scale almost at once in New York. A waterproof coating was given it to prevent further weathering, but its life will be greatly shortened unless it is entirely enclosed. The companion obelisk on the Victoria Embankment of the Thames in London, where frost action is rare, does not show signs of decay as yet—and that in spite of the fact that it spent a number of years on the bottom of the ocean.

An excellent place to study the life of the polish on a stone is in the Egyptian section of the British Museum. The Egyptians learned to polish stone about 1500 B.C. Stones belonging to that period, having remained partly buried in the sand, show a perfect polish on the buried part but have lost it on that exposed. To what extent the polish was cut away by wind action is unknown. The dry climate of Egypt was the dominant factor in preserving it.

The *use* to which a stone is put also affects its durability. If a soft stone is subjected to mechanical wear, its life is short. The wear on floors and steps is great, especially in public buildings. Sandstone and limestone in sidewalks wear rapidly. Marble is extensively used for floors and steps and always shows the effect of wear in a few years. The life of stone steps is frequently as short as 5 years. A sandstone cemented with silica is resistant and thus is suitable for sidewalks, but one having a calcite cement rapidly becomes rough and irregular.

KINDS OF ROCK USED AS BUILDING STONE

Almost every type of rock is suitable for use as building stone, and a list of those so used would be long. The most common kinds are *granite* (and closely related types of igneous rocks), *limestone*, *sandstone*, *marble*, and *slate*. For crushed stone, chiefly limestone, *basalt*, *trap rock* (a type of basalt), and granite are used. For special purposes, some rare kinds of rocks, such as *serpentine*, *travertine*, and *onyx*, are employed.

GRANITE AND OTHER IGNEOUS ROCKS

The quarryman includes under the term "granite" not only true granite (a crystalline rock composed of feldspar and quartz) but also other crystalline rocks, such as *syenite* (composed of feldspar without



FIG. 204.—Map showing most of the granite (and related crystalline rocks) quarries in the United States. (Data U. S. Geol. Survey Bull. 624.)

quartz); *gneiss* (a banded rock having a mineral composition like either granite or syenite); and also dark crystalline rocks, such as *diorite*, *gabbro*, *diabase*, and *basalt*. The last two are usually called "trap rock"; and the first two, "black granite." Occasionally, some light-colored volcanic rocks, such as *tuff*, *felsite*, *rhyolite*, and *andesite*, are included with the granites.

Physical Properties of Granite.—Granite possesses all the physical properties essential in a good building stone so is an ideal stone. The color of most granites is gray, but there are also pink, red, green, and nearly white varieties. The strength of this stone is high, and it is impervious to water. It takes a high polish (increasing its beauty) and retains it for centuries.

Distribution of Granite in the United States.—Granites are of widespread occurrence in the United States, as can be seen from the accompanying map (Fig. 204). Quarries are located in nearly every state along the Atlantic Coast as far south as Georgia. The New England states produce about 45 per cent of the granite quarried in the United States. There are important quarries in the following localities: Penobscot Bay area, *Maine* (furnishing building and curbing material); Rockport, Quincy, Becket, and Milford, *Massachusetts* (furnishing dressed and rough building stone and monumental stone); Hillsboro, Carroll, Grafton, and Merrimack counties in *New Hampshire* (furnishing rough building stone); Barre, *Vermont* (furnishing monumental stone); and Westerly, *Rhode Island* (furnishing monumental stone).

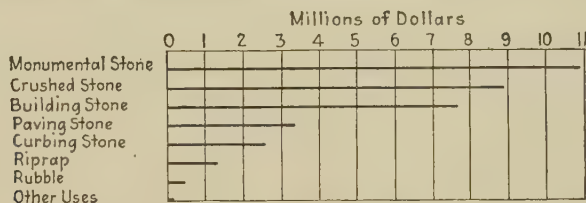


FIG. 205.—Graph showing value of different uses to which granite was put in the United States in 1927. (Data from *U. S. Mineral Resources*, 1927, Part 2, p. 217.)

In the Mississippi Valley, *Wisconsin* and *Minnesota* are the largest producers of granite; minor amounts are quarried in southeastern *Missouri*, southern *Oklahoma*, and central *Texas*.

There is an abundance of granite in all the western states, but *California* is the only important producer. Considerable basalt is quarried for crushed stone in California, Oregon, Washington, and Idaho.

Uses of Granite.—As granite is an ideal building stone, it is widely used in all countries. The demand for it as a monumental stone is growing steadily and is now nearly treble that of marble for the same purposes. Its uses in the United States in 1927 are shown by Fig. 205.

LIMESTONE

The great abundance of limestone, the ease with which it is quarried and dressed, and its general durability make it a rock that is used extensively as a building stone. Limestone is composed essentially of calcite, but it may also contain other minerals. If the amount of MgCO_3 is large (20 per cent or more), the rock is called a "dolomite." Both limestone and dolomite are widely used for building purposes, rubble, riprap, and crushed stone; but for most chemical uses, such as sugar making, the pure calcium limestone is essential.

Mode of Occurrence of Limestone.—Limestone is a stratified rock and occurs in beds of varying thickness. Where the beds are horizontal,

the cost of quarrying is greatly reduced, especially if they are not covered by a too thick overburden. Joints are common and are of value to the quarryman. Not all the beds in a quarry are necessarily suitable for building material. Some are undesirable because of impurities they contain, as, for instance, the chert nodules in certain beds of limestone at Carthage, Missouri. The presence of pyrite in limestone is bad, not only because upon weathering pyrite discolors the rock, but also because the sulfuric acid set free in the process attacks the stone. In the stone of Bedford, Indiana, some beds contain stylolites, which render the stone undesirable. In some regions, undesirable rocks may be interbedded with the limestone.

Physical Properties of Limestone.—Limestones show a wide range in texture, color, strength, hardness, and durability. The texture ranges from coarse to very fine grained, the latter predominating. The coarse-grained limestones (and less commonly the fine-grained ones) are similar to the metamorphic marbles and are frequently sold as marble. The color of a pure limestone or dolomite is white, but carbonaceous matter changes this to some shade of gray or even to black. More rarely, due to iron oxides, the color is buff, tan, pink, or red. The strength of most limestones is ample for the uses to which they are put. The Carthage limestone has shown a crushing strength of over 20,000 pounds per square inch. Most chalk does not exhibit sufficient hardness to withstand much hard usage and, hence, is seldom used. Limestones generally have a long life. If properly placed in a wall, they withstand frost and heat action well; and, as the majority are only slightly porous, they do not absorb much water. The stone of Bedford, Indiana, and the coquina rock of Florida, however, have higher porosities, the former 4 to 5 per cent, and the latter about 25 per cent.

Varieties of Limestone.—Many kinds of "limestone" are on the market. *Dolomite* has been mentioned above. *Chalk* is a soft, porous fine-grained limestone. *Oolitic limestone* is made up of small, rounded grains of calcium carbonate. *Travertine* or *calcareous tufa* is a very porous or cellular limestone deposited by springs or streams. *Coquina* is composed of fossils and fragments of shells rather poorly cemented. Very little is used for building on account of the high porosity and low strength of the rock. It occurs abundantly in Florida where it is used locally to a limited extent. *Fossiliferous* or *shell limestones* contain fossils. *Onyx* is a variegated and banded limestone found in caves or deposited by springs and streams.

Distribution of Limestone in the United States.—Figure 202 (p. 484) shows the distribution of limestone in the United States east of the Rocky Mountains and the few outcrops in California. Limestone is equally abundant throughout the western states; but, as it is less extensively quarried there, the deposits have not been mapped.

Age of Limestones.—Limestones are of all ages from the Cambrian to the Tertiary. The Mississippian formations, especially in Indiana and Missouri, furnish an abundance of building material.

Uses of Limestone.—The relative importance of the different uses of limestone in the United States in 1927 is seen from the accompanying table:

TABLE 97.—USES¹ OF LIMESTONES IN THE UNITED STATES, 1927²

Use	Quantity, short tons	Value
Crushed stone.....	65,080,400	\$ 63,411,465
Building stone.....	1,278,620	18,820,045
Fluxing stone.....	21,660,820	15,977,484
Agriculture.....	2,206,470	3,360,704
Alkali works.....	3,848,490	2,449,284
Riprap.....	2,185,380	2,119,557
Asphalt filler.....	420,860	1,343,987
Sugar factories.....	483,800	881,370
Whiting substitute.....	124,840	551,915
Paper mills.....	289,010	436,204
Refractory stone (dolomite).....	434,160	424,140
Glass factories.....	247,210	420,415
Rubble.....	226,280	400,790
Stucco, terrazzo, and artificial stone.....	98,180	348,797
Filter stone.....	271,800	272,834
Road base.....	198,660	236,317
Poultry grit.....	33,350	198,144
Calcium carbide works.....	316,960	164,875
Curbing, flagging, and paving.....	18,670	134,360
Magnesia works (dolomite).....	69,940	115,932
Coal mine dusting.....	28,410	91,495
Mineral food.....	30,470	80,274
Mineral (rock) wool.....	15,390	12,962
Carbonic acid works.....	8,860	7,566
Roofing gravel.....	5,620	6,658
Other uses (stone for ammonia, baking powder, lime burners, nitrates, phosphates, powder, purification of copper, reduction of aluminum ore, soap, sulfuric acid, and uses not specified).....	79,620	172,250
Total.....	99,662,270	\$112,439,824

¹ Exclusive of the limestone used in lime and cements.² U. S. Mineral Resources, 1927, Part 2, pp. 231-234.

Of the \$18,820,000 worth of limestone used for building purposes, the district of Bedford, Indiana, furnished over \$16,500,000 worth.

The following table includes the amounts of limestone used in the manufacture of cements and lime. The amount of limestone going into

cements and lime is a little less than one-third of the total amount used for all purposes.

TABLE 98.—LIMESTONE USED FOR ALL PURPOSES IN THE UNITED STATES, 1927¹

Use	Amount, short tons
Uses given in Table 97.....	99,662,270
Portland cement (including cement rock used in its manufacture).....	43,800,000
Natural cement or cement rock.....	395,000
Lime.....	8,830,000
Total.....	152,687,270

¹ *U. S. Mineral Resources*, 1927, Part 2, p. 234.

MARBLE

Under the term "marble" are included not only the crystalline and metamorphosed limestones and dolomites but also serpentine, onyx marble, and travertine. Travertine is really a limestone, though it is sold as marble; but serpentine has an entirely different composition.



FIG. 206.—Looking down into marble quarry of the Vermont Marble Company at Florence, Vermont. (Photograph by W. A. Tarr.)

Marble (proper).—True marble is a limestone that has undergone recrystallization. Any limestone, whether crystalline or dense, is called marble in the building trade. The crystalline varieties are more translucent and have greater depth on a polished surface. The physical properties of marble are very similar to those of limestone. One notable feature of marble is its variability of color, which is rarely distributed uniformly through the rock. It occurs as streaks, bands, and spots. The marbles, as a rule, are all dense rocks. All the marble marketed is massive.

Distribution of Marble in the United States.—Marble is not so

widely distributed as limestone, as it is confined largely to areas where metamorphic processes have been effective. An important marble-producing belt extends from Vermont to Georgia. Vermont (Fig. 206) at the northeast end of this belt is the leading producer, and Georgia at the other end is second. Many beautiful variegated marbles are produced in this region.

Vermont produces a great variety of marbles. The quarries are located mainly in Bennington, Rutland, and Addison counties. Two other localities are worth noting: Swanton, Franklin County (producing a reddish dolomite marble); and Isle la Motte, Grand Isle County (producing a black calcite marble). The Rutland quarries produce a wide range of colored marbles used for interior decoration. Proctor, Brandon, and Dorset are important Vermont centers of marble production. Dickens County in *Georgia* produces a gray marble and a fine-grained white one.

Tennessee is the third state in the production of marble, and *Missouri*, producing a coarsely crystalline limestone, is fourth. The mountainous

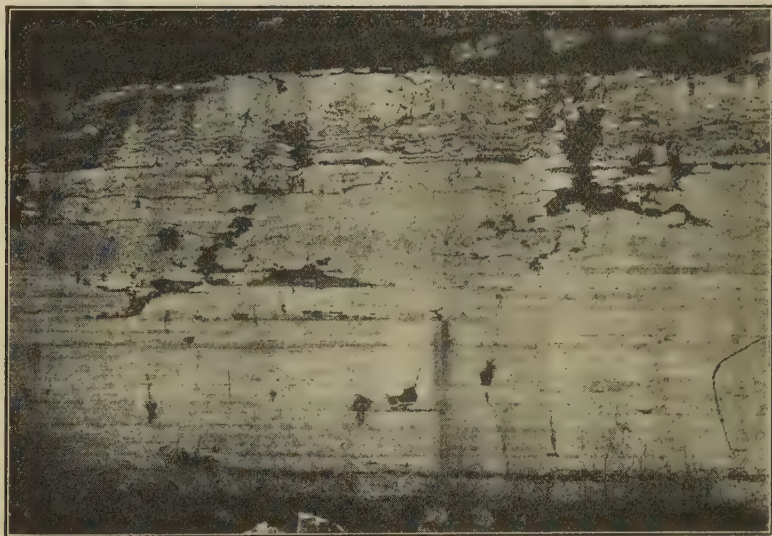


FIG. 207 A.—Travertine in the quarries a few miles northeast of Rome, Italy. The travertine was deposited by waters of hot springs. Note the uniform banding of the lower beds and the wavy character of the top beds. (Photograph by W. A. Tarr.)

areas of the west also produce some marble. In recent years, Gunnison County, *Colorado*, has been producing a pure white marble suitable for statuary purposes.

Imported Marble.—In 1927, the United States imported \$3,500,000 worth of marble, travertine, and onyx, over 75 per cent of which came from *Italy*. Much of it was the travertine (Fig. 207 A) which is quarried a few miles northeast of Rome. It is shipped in large blocks (Fig. 207 B) and is cut and dressed in the United States. Some Carrara marble (Fig. 208 A and B) is also imported for statuary purposes.

Uses of Marble.—Unlike granite the major use of which is for monumental purposes, marble finds its chief application as a building material, dominantly as a finished product. The value of that used for different

purposes in the United States in 1927 is shown in the accompanying graph (Fig. 209). The reason for the greater use of granite for monu-



FIG. 207B.—Blocks of travertine in the travertine quarries a few miles northeast of Rome, Italy. These blocks are ready for shipment to America. (*Photograph by W. A. Tarr.*)



FIG. 208A.—View in one of the hundreds of quarries producing Carrara marble near Carrara, Italy. Note the massiveness of the marble. The sawed face at the left was cut by a wire saw. (*Photograph by W. A. Tarr.*)

ments is its greater durability. Few marble monuments retain their polish more than 30 or 50 years, and they may lose the entire inscription

in 100 to 200 years, depending upon the local atmospheric conditions. For interior decoration, marble has no superior.

Serpentine.—Serpentine is a hydrous magnesium silicate. It may also contain pyrite, magnetite, calcite, magnesite, and various rare



FIG. 208B.—Primitive method of moving blocks of marble in the quarries of Carrara, Italy. The men are dragging the block of marble along on short timbers (seen in foreground) by means of a wire cable. No rollers are used; the block slides on the timbers. The marble is hauled to the railroad on carts drawn by oxen. (Photograph by W. A. Tarr.)

minerals. It is commonly called “verde antique” marble by the building trade, although the original, genuine verde antique used by the Greeks and Romans was a green porphyry containing feldspar phenocrysts up to an inch in length. Included with the serpentine is a rock composed of

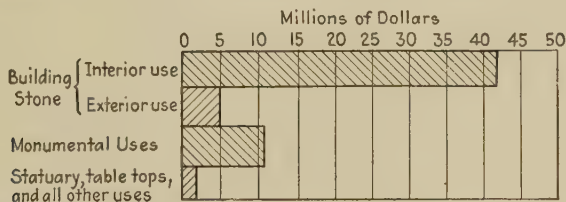


FIG. 209.—Diagram showing the value of marble, by uses, in the United States in 1927 (Data from U. S. Bur. Census.)

calcite or dolomite and serpentine. It is known as “opicalcite” (or, also, as verde antique marble). The amount of serpentine in opicalcite may be less or greater than that of the carbonates; and, as the serpentine increases in amount, the rock grades into relatively pure serpentine.

Characteristics of Serpentine.—Serpentine is usually green or yellowish green but may also be red, brown, or black. The color is not uniformly

distributed, which produces a mottled effect. In most quarries, it is difficult to obtain large blocks of serpentine because of the numerous joints in the rock. Serpentine is, therefore, marketed chiefly after being sawed into slabs of varying thicknesses. The rock takes a good polish and is extensively used for interior decoration.

Distribution of Serpentine in the United States.—Deposits of serpentine occur in *Maryland, Massachusetts, New Jersey, Pennsylvania, Vermont, Georgia, California, and Washington*; and all but Georgia made a production in 1927. In value, this production totaled \$736,000.

Onyx Marble.—Onyx marble is a mottled or banded calcareous rock that has been formed in springs and streams (travertine) or as stalagmites in caves. *Arizona, Kentucky, Utah, California*, and several other states contain fairly important deposits, but most of the onyx used in the United States is imported. It is used entirely for decorative purposes.

SANDSTONES

Sandstones are clastic rocks composed essentially of quartz. They are cemented by silica (quartz), calcite, or iron oxides. They may also contain feldspar (the sandstone is then called *arkose*), mica, and pyrite. The presence of pyrite makes a sandstone undesirable, because it may alter to iron oxides which discolor the stone. *Quartzites* are sandstones that are so firmly cemented with quartz that the rock breaks *through* the grains instead of *around* them as it does in a sandstone. *Blue stones* and *flagstones* are sandstones which split easily. They are widely used for paving and curbing.

Physical Properties of Sandstone.—Sandstones range from fine-grained to coarse-grained in texture, and they may be conglomeratic. Unless well cemented, they are porous and can absorb 8 to 10 per cent of water. The color of sandstone may be white, gray, yellow, brown, or red. Dark gray and black (due to carbonaceous matter) are rare. Many sandstones are very poorly cemented and consequently are soft and crumble easily. As the amount of cement in sandstone increases, the rock becomes hard and resistant and, when fully cemented, as in quartzite, is the hardest of all building stones. The crushing strength of sandstone ranges from 2,500 to 15,000 pounds per square inch, averaging about 8,000 or 9,000 pounds. A recent study by the U. S. Bureau of Standards has shown that if an average sandstone is immersed for several hours in melted sulfur, the sulfur soaks into the stone and further cements it. The resulting product has a crushing strength of 30,000 pounds per square inch, or about that of a strong granite. Sandstones are durable. Their chief fault as building stones is their porosity, if poorly cemented. The mistake is often made of setting sandstone on edge in a wall. In this position, it easily scales off parallel to the bedding planes, especially if

much mica is present. Resurfacing must then be resorted to in order to regain a satisfactory appearance.

Age of Sandstones.—Sandstones are of all geologic ages from pre-Cambrian to Pleistocene. Those used for building stone come mainly from the pre-Cambrian, Paleozoic, and Mesozoic formations, because the sandstones of these formations are well cemented. The Connecticut brownstone is of Triassic age. Its use has greatly declined in recent years.

Distribution of Sandstone in the United States.—The Berea sandstone (Mississippian age) from northeastern *Ohio* is at present the kind most extensively used for building purposes and curbing. *Pennsylvania* is the second state in the production of sandstone, but her product is used dominantly for ganister (a furnace lining) and for crushed stone. *New York*, *California*, *Washington*, *Wisconsin*, and *Virginia* all produce considerable quantities of sandstone. On the whole, the production in the United States has been declining in recent years.

Uses of Sandstone.—Nearly equal amounts of sandstone are employed for building purposes (both rough and dressed stone) and for crushed stone. The next important uses of sandstone are for curbing and as refractory stone (ganister). Others are for rubble, flagging, riprap, railroad ballast, and many minor uses.

SLATE

Slate is a rock that has a well-developed cleavage, which permits its being split into thin sheets suitable for many purposes.

Physical Properties of Slate.—Slates have a wide range of colors. Black, gray, and green are the most common, but there are also red, purple, variegated, and “freak-colored” slates. The black and gray slates owe their color to graphite; the green ones, to chlorite; and the red and purple, to hematite. Mixtures of these coloring agents give many other shades, and the colors, when irregularly distributed, produce the variegated slates. The texture of slate ranges from fine to coarse grained. If it is very coarse grained, the slate grades into *phyllite*. Slate has excellent cleavage due to the parallel arrangement of its chief mineral constituents, and the cleavage surfaces have a bright luster for the same reason.

Mineral Composition of Slate.—The chief mineral constituent of slate is muscovite. In the green slates, chlorite and the mica are the chief constituents. Quartz is abundant in all slates, and chlorite and hematite are next in abundance. Pyrite and various carbonates (of iron, lime, and magnesia) are present in some slates. If the iron carbonate is sufficiently abundant, the slate fades after several years of exposure. As a result, slates are usually classified as unfading (low iron carbonate content) and fading (high iron carbonate content).

Origin of Slate.—Slates are the result of metamorphic processes upon beds of clay and shale either of which may contain considerable fine sand.

Sands are often interbedded with the clay, as shown by the quartzite bands which run through slate beds. During the process of metamorphism, the kaolin and other clay minerals of the original clay are converted into mica; the colloidal silica, into quartz; the magnesium and some of the kaolin, into chlorite; and the iron, into hematite. Pressure forces the newly formed mica and chlorite sheets into a parallel arrangement, which produces the excellent cleavage of slates. These cleavage planes are usually at an angle to the bedding planes. This angle is rarely less than 5 to 10° (in the Pennsylvanian slates), and it may be 90° . Not uncommonly, the original bedding planes are folded, but the cleavage planes are parallel regardless of the position of the bedding planes, and intersect them at all angles.



FIG. 210.—Map showing the location of the productive slate and slate granule areas in the United States and the prospective areas. (Data from U. S. Mineral Resources.)

Distribution of Slate in the United States.—As intense metamorphism is necessary to the formation of slates, it is to be expected that the most important slate areas would be in those regions where there has been much folding, such as the Appalachian belt extending from Maine to Georgia (Fig. 210). Slates occur in other areas in the United States where clayey rocks have been metamorphosed.

Pennsylvania and *Vermont* produced 79 per cent of the slate sold in the United States in 1928 (over 60 per cent of this production was used for roofing). All the production in Pennsylvania comes from Northampton and Lehigh counties, save that crushed and sold as granules and

slate flour. This Pennsylvania area is the leading producer of blackboards, bulletin boards, and slates. The Vermont district (Rutland County) should also include Washington County, *New York*, as the slate belt is continuous in the two counties. This area produces all the colored slates used for roofing. Green and purple are the dominant colors of the slate in Vermont, and red in New York, but both states produce slates of numerous other colors. Variegated slates and those having freak colors are in considerable demand just at present (1929). Large quantities of sea-green roofing slate are produced in Vermont. The quarries are located near Pawlet, West Pawlet, Poultney, Fair Haven, and Castleton in Vermont; and near Granville in New York. Other states producing slate in this belt are *Maine, Virginia, Maryland, Tennessee, and Georgia*.

Uses of Slate.—The dominant use of slate is for roofing, 49 per cent of the total production in the United States in 1928 being so used. Slate for roofing is sold by the “square,” which equals 100 square feet. A square of slate $\frac{3}{16}$ inch thick weighs about 800 pounds; and one $\frac{1}{4}$ inch thick weighs 1,000 pounds. Sizes of slate shingles run normally from 6 by 10 to 18 by 36 inches.

The next most important use of slate in this country in 1928 was for blackboards and bulletin boards. Slate for electrical purposes (switchboards chiefly) ranks fourth among the uses, and numerous others follow. The following are some of the most important of these minor uses: school slates, billiard-table tops, vats, stationary tubs, laboratory-table tops, mantles, grave linings, wainscoting, hearths, chimney and well caps, memorial tablets, bread boards, and refrigerator shelves.

Waste in the Production of Slate.—The quarrying, splitting, and trimming of slate has ever been attended by enormous waste. Some years ago, this waste was 80 per cent of the material quarried. The slate producers have long sought a use for this waste material, but it has been only in recent years that an important one has arisen. The waste slate is now crushed to form slate granules and flour. The former is used in manufacturing the prepared green, red, gray, and variegated shingles, which are so extensively employed at present. Granules constituted over 23 per cent of the total value of slate products in 1928 in the United States. The slate flour is used as a filler. Slate producers are now using machinery for quarrying and in this way are also helping to reduce the enormous waste in slate production.

Selected Readings on Stone

- BUCKLEY, E. R.: *The Building and Ornamental Stones of Wisconsin*, Wis. Geol. and Nat. Hist. Survey Bull. 4, 1898.
— and BUEHLER: *The Quarrying Industry of Missouri*, Mo. Bur. Geol. and Mines, 2d ser., vol. II, 1904.

- DALE, T. N.: Commercial Marbles of Western Vermont, U. S. Geol. Survey *Bull.* 521.
 —: The Chief Commercial Granites of Massachusetts, New Hampshire, and Rhode Island, U. S. Geol. Survey *Bull.* 354, 1908.
 —: Slate Deposits and Slate Industry of the United States, U. S. Geol. Survey *Bull.* 275, 1906; *Bull.* 586, 1914.
 ECKEL, E. C.: "Building Stones and Clays," New York, 1912.
 MERRILL, G. P.: "Stones for Building and Decoration," The Macmillan Company, New York, 1904.
 PARKS, W. A.: Report on the Building and Ornamental Stones of Canada, Canada Dept. Mines, Mines Branch, *Rept.* 100, vol. I, 1912.
 RIES, H.: "Building Stones and Clay-products," John Wiley & Sons, Inc., New York, 1912.
 —and WATSON, "Engineering Geology," pp. 428-492, John Wiley & Sons, Inc., New York, 1914.
U. S. Mineral Resources, 1911, Part 2, pp. 723-834; 1912, Part 2, pp. 709-818; 1913, Part 2, pp. 1285-1410; 1918, Part 2, pp. 1189-1313.
 WATSON, T. L.: Granites in the Southern States, U. S. Geol. Survey *Bull.* 426, 1910.

There are many U. S. Geological Survey and state geological reports on building stones. Maps showing the location of quarries in the United States are given in *U. S. Mineral Resources* for 1911, 1912, and 1913. The trade journals on stone also contain much interesting information.

SAND AND GRAVEL

Sand and gravel are detrital, fragmental materials. The former is composed of grains between 0.2 (2 to 3 millimeters) and 0.02 inch (0.5 millimeter) in diameter. The latter includes the material from coarse sand (0.125 inch in diameter) to pebbles 2.5 to 3 inches in diameter. A material composed of particles from 0.125 to 0.25 inch in diameter (the coarsest sand particles and the finest gravels) is called "torpedo sand." The term "sand" includes many different kinds, such as quartz sands, gypsum sands, coral sands, volcanic sands, black sands, and many others.

Materials in Sands and Gravels.—The sand used as a structural material consists almost exclusively of quartz grains. For some purposes, other minerals, such as feldspar, mica, and iron oxides, may be present; but for most uses, the sand should be a pure quartz sand. Gravel consists dominantly of quartz pebbles, but it may also contain pebbles of other minerals and of all the various rocks. Quartz is a very durable mineral so in the process of weathering is left unaltered. During the subsequent process of transportation, the coarser quartz grains become separated from the finer clay particles, and the results are deposits of sand and gravel. The accumulations of these materials are also known as "detrital deposits."

Mode of Occurrence of Sand and Gravel.—Sand and gravel occur as beds interbedded with other sedimentary rocks, such as shale, limestone, and conglomerate; as beds, lenses, and pockets in the flood-plain deposits of rivers; as deposits made in the channels of rivers and smaller

streams; as wind-made deposits along rivers, lakes, and the seashore; and as deposits made by water from the melting of glaciers. In some of these, the materials may occur well sorted and be of a high degree of purity; in others, they are of such irregular sizes that they must be sized before using; and in still others, the amount of clay and other fine material may be so great as to make it necessary to wash the sand or gravel before using it. Over 76 per cent of the sand and gravel used in 1927 in this country had been washed.

Preparation for Use.—Most sand requires a minimum of treatment before using. Its mode of occurrence may be such that it must be mined, as at Pacific, Missouri, where glass sand is secured. It may be obtained from open pits or from river channels by means of dredges, clam buckets, or sand pumps. If it must be sized, it is put through a series of screens. Usually the screening is accompanied by washing, as the use of water facilitates the movement of the sand through the screens and at the same time cleans it by removing the clay and organic materials. In the preparation of most of the special sands, the sizing and washing must be carried on with extreme care.

Uses of Sand and Gravel.—The chief uses to which sand and gravel are put are as *building* and *paving materials*, but there are also a number of uses requiring sands having special properties. Some of these special sands are *glass sand*, *molding* (foundry) *sand*, *abrasive sands* (discussed

TABLE 99.—PRODUCTION AND VALUE OF THE SAND AND GRAVEL BY USES IN THE UNITED STATES, 1927¹

Use	Amount, short tons	Value
Sand:		
Glass.....	2,171,693	\$3,257,790
Molding.....	4,194,975	4,458,508
Building.....	40,737,377	22,198,767
Paving.....	35,606,622	17,767,491
Grinding and polishing.....	1,686,762	21,193,690
Fire or furnace.....	410,801	452,835
Engine.....	2,618,890	1,640,736
Filter.....	74,674	155,137
Other.....	6,086,545	2,166,444
Total.....	93,588,339	54,291,398
Gravel:		
Building.....	30,432,031	21,947,666
Paving.....	44,891,975	29,887,365
Railroad ballast.....	28,541,924	9,403,357
Total.....	103,865,930	61,238,388
Grand total.....	197,454,269	115,529,786

¹ U. S. Mineral Resources, 1927, Part 2, p. 161.

under Abrasives), *fire or furnace sand, engine sand, filter sand, roofing sand, flooring sand, railroad ballast, potters' sand, standard sand, sand for chemical uses, and sand for making quartz powders and fillers.* The use of some of these sands is not strictly structural, but their description and uses are given in this section in order to preserve the unity of the discussion. Exceptions are made of certain sands whose major uses permit placing them under another section.

Table 99 shows the production and value of sand and gravel by uses in the United States in 1927.

BUILDING AND PAVING SANDS AND GRAVELS

The most important application for sand and gravel is in building construction, about 35 per cent of the 1927 production in the United States going into that use. A clean sand is required for this purpose, and many builders prefer an angular sand (sharp sand) to one with rounded grains. The sand is used in concrete and in various mortars.

About 41 per cent of the sand and gravel produced in the United States in 1927 was used in paving; most of this was put into concrete, but a part was for graveling roads. With the tremendously large road-building program still underway throughout the United States, the demand for sand and gravel for paving will undoubtedly increase. Sand and gravel for road making need not be so clean as those used for building purposes. Some states permit as much as 3 per cent of clay in road-making materials. Deposits of sand and gravel suitable for building and paving uses are of such widespread occurrence that long hauls are fortunately seldom necessary.

MOLDING SANDS

Molding sands are employed in foundries for making the mold of the pattern of the castings to be reproduced in metal.

Properties of Molding Sand.—As the sand must retain the form of the pattern after it has been removed, cohesiveness is an essential property of a molding sand. Furthermore, the sand must be sufficiently permeable to allow the gases to be given off from the cooling metal. It must also be refractory, so as not to fuse where it is in contact with the hot molten metal. Its texture must be adapted to the particular kind of casting used. Coarse molding sand is used for large, heavy castings and fine sand for the smaller ones. In addition to being used as the mold, the sand is also employed as cores if the casting contains hollow spaces. Core sands usually need some artificial binder added to them.

Special Kinds of Molding Sands.—*Steel-molding sand* is a clean white or yellowish-white sand. It has no bond; hence, clay, molasses water, or other material must be added as a binder. *Iron-molding sands* are lower in grade than steel-molding sands. They are usually brown

in color and have good bonding properties. For molding brass, bronze, copper, or aluminum, a very fine sand with a good bond is used, because the finest details of the pattern must be imprinted in the mold in order to show in the casting and, also, because the surface must be smooth. The value of a particular sand for molding purposes can be determined only by a series of experimental tests.

Distribution of Molding Sand in the United States.—Large quantities of molding sands are used in the foundries in this country, and most of them are secured from sources relatively near. Special grades of sand may require a long haul, however. Thirty-one states produced molding sand in 1927. The states leading in production were *New York, Ohio, Pennsylvania, New Jersey, Illinois, Michigan, and Indiana.*

GLASS SAND

A large amount of sand is used annually in the manufacture of glass. The common kinds of glass, such as common tableware, bottle, plate, and window glass, contain from 65 to 75 per cent silica.

Composition of Glass Sands.—Glass making is one of the special uses that require a sand composed of pure *quartz*. An absolutely pure quartz sand is unknown, as there are always small quantities of foreign materials present. The following table from Fettke¹ shows the range in composition of various sands:

TABLE 100.—PERCENTAGE COMPOSITION OF SANDS OF VARIOUS QUALITIES¹

Quality	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO + MgO
	Minimum percentage	Maximum percentage		
First (for making optical glass).....	99.8	0.1	0.02	0.1
Second (for making flint glass used for containers and tableware).....	98.5	0.5	0.035	0.2
Third (for making flint glass).....	95.0	4.0	0.035	0.5
Fourth (for making sheet glass for rolled and polished plate).....	98.5	0.5	0.06	0.5
Fifth (for making sheet glass for rolled and polished plate).....	95.0	4.0	0.06	0.5
Sixth (for making green glass for containers and windows).....	98.0	0.5	0.3	0.5
Seventh (for making green glass).....	95.0	4.0	0.3	0.5
Eighth (for making amber glass for containers).....	98.0	0.5	1.0	0.5
Ninth (for making amber glass).....	95.0	4.0	1.0	0.5

¹ From the work of C. R. Fettke based on ignited samples.

¹ FETTKKE, C. R., *American Glass Sands, Their Properties and Preparation*, Am. Inst. Min. and Met. Eng. *Trans.*, 1531-H, 1926.

The *alumina* in glass sands is usually present in clay, more rarely in muscovite or feldspar. In certain glasses, the alumina content must be low, but for common ones a small amount is not harmful.

The *iron oxides* are the most detrimental impurities of glass sand, whether the iron is ferrous, which gives a green color to the glass; or ferric, which gives a yellow tint. In addition to coloring the glass, iron reduces the brilliancy and transparency of the product. As the above table shows, the allowable amounts are in hundredths of 1 per cent. The iron can be present as a coating of limonite or as any one of several iron-bearing minerals. As glass is made under chemical conditions of reduction, the ferric oxides are reduced to the ferrous, and therefore green is the

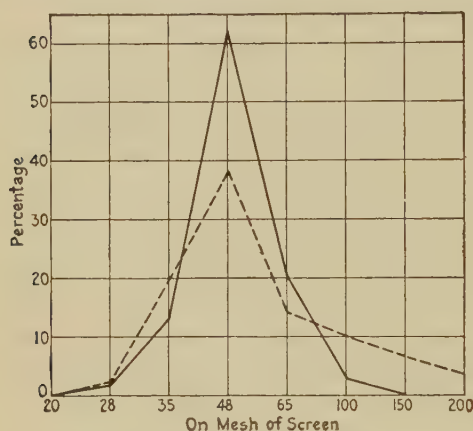


FIG. 211.—Curves showing the percentage composition of the grain sizes in the two most important glass sands in the United States. A, Oriskany sandstone from Mapleton Depot, Huntingdon, Pennsylvania. B, St. Peters sandstone from Ottawa, La Salle County, Illinois. (Data from Feltke, *Trans. Am. Inst. Min. and Met. Eng.*, No. 1531-H, 1926.)

probably due to the slow formation of manganese silicate, which is pink.

The amount of *lime* present in the average glass sand is so small as to be unimportant. *Magnesia* is also rare and is far more abundant in even the purest limestones used in manufacturing glass. *Alkalies* are used in making all common glasses; hence, would do no harm if present in the glass sand.

Size and Shape of Grains in Glass Sand.—The size of the sand grains in glass sands is important. Sands with very fine or very coarse grains are unsuitable. It is of still more importance, however, that the sand grains be of uniform size. In general, all the sand should go through a 20-mesh screen, and not more than 5 per cent should pass a 100-mesh screen. Figure 211 shows the percentage composition of the grain sizes of the two best glass sands in the United States.

dominant color of glass. Ordinary window glass is apparently colorless; but, if it is viewed from the edge, the green tint is very evident. If the amount of iron oxide present is small, decolorizing agents may neutralize it. Manganese dioxide (sometimes called the glass-maker's "soap"), nickel oxide, arsenic trioxide, and selenium are used for this purpose. Glass that has had manganese dioxide added becomes, after long exposure to the sun's rays, a delicate amethystine or lavender color. Such colored glass is frequently seen in the windows of old houses and is highly prized by the owners. This color is

The shape of the grains in a glass sand is not so important; some glass manufacturers prefer angular grains; and others, rounded ones.

Distribution and Geologic Age of Glass Sands in the United States.—Sand suitable for glass making is not widely distributed in the United States. The Oriskany sandstone (Devonian) in *West Virginia* and *Pennsylvania* and the St. Peter sandstone (Ordovician) in *Illinois* and *Missouri* produced 74 per cent of the 1927 production. *New Jersey*, where the sand came from the Tertiary formation, was another important producer. Only small quantities of glass sand come from other geological horizons in this country, and even the Oriskany sandstone is not of value everywhere.

The Oriskany Sandstone.—

The two important areas of Oriskany sandstone are in Huntingdon and Mifflin counties in central Pennsylvania and in Morgan County in northeastern West Virginia. The sandstone in the Pennsylvanian area ranges from 130 to 170 feet in thickness and dips from 60 to 65° to the west. The rock was originally a quartzite; but, through weathering, it has disintegrated into a friable sandstone (see Fig. 212 A).

In West Virginia, the Oriskany sandstone ranges in thickness from 185 to 210 feet and dips about 48° to the east. The most important locality is near Berkeley Springs in Morgan County. The sand of both areas is quarried, crushed, washed, dried, and screened. The curve in Fig. 211 gives the percentage composition of grain sizes of this valuable glass sand.

The St. Peter Sandstone.—The St. Peter sandstone is quarried in Kendall, La Salle, and Ogle counties in Illinois, but most of the production in the state comes from Ottawa in La Salle County. The sandstone is from 120 to 200 feet thick and lies nearly horizontal. It is very pure, in places exceeding 99 per cent silica. It is friable and is pure white. The grains are remarkably well rounded (see Fig. 212 B). The material is easily loosened and is hydraulicked and pumped out by sand pumps. It is then dried and screened. Four products are made from it, one of which is sold as glass sand.

The St. Peter sandstone in Missouri occurs in Franklin, Jefferson, St. Charles, and St. Louis counties. The main production comes from



FIG. 212.—A, Glass sand from the Oriskany sandstone, Mapleton, Pennsylvania. B, from the St. Peters sandstone, Ottawa, Illinois, (After Feltke, *Trans. Am. Inst. Min. and Met. Eng.*, No. 1,531-H, 1926.)

the vicinity of Pacific in Franklin County and near Crystal City in Jefferson County. The bed is from 60 to 100 feet thick. The sandstone is white and friable, and the grains are well rounded. The rounding was evidently done by the wind. The sandstone is both quarried and mined.

Other Glass Sands.—The New Jersey sands are unconsolidated and occur in horizontal beds, some of which are 90 feet thick. They have only a thin overburden. The major production is made near Bridgeton. The sand is of a lower grade than that from the Oriskany and St. Peter formations, but it is suitable for making high-grade bottles, pressed ware, and window glass.

Most of the factories using glass sand are located near these deposits. The western part of the United States has very little good glass sand.

Manufacture of Glass.—Glasses vary in composition. Most common glass is soda-lime glass. Other kinds are of special grades and have different compositions. A standard glass has about the following percentage composition:

	Percentage
5 Na ₂ O.....	41.53
5 CaO.....	36.36
3 SiO ₂	23.37

Common glass is made by fusing sodium carbonate or sodium sulfate (salt cake), calcium carbonate (pure limestone), and quartz sand. This mixture is called the "batch." The fusing is done in various types of furnaces, which are lined with a refractory clay (called "glass-pot clay"). The batch is raised to a temperature sufficiently high to melt the three ingredients and allow them to react with one another to form glass. The temperature is then raised to make the melt more fluid, which makes it easier for the gas (CO₂) to escape. The soda and lime unite with part of the silica to form silicates. The remainder of the silica dissolves slowly, increasing the viscosity of the batch. The melt is cooled and poured into the forms desired or is pressed or blown (by compressed air) into them.

Special kinds of glass, such as colored glass, require special treatment. Quartz glass is being made rather extensively at present. Because of its low coefficient of expansion (it is possible to plunge white-hot quartz glass into water without breaking it), it is very valuable for various chemical wares, such as tubes, crucibles, and dishes. Other uses of quartz glass are for quartz lights and window glass. Quartz window glass is used in hospitals for subjecting patients to sun baths.

Uses of Glass.—The uses of glass are so common that little need be said about them. Optical glass is the highest quality and is employed for lenses in telescopes, microscopes, reading glasses, and eyeglasses. Years are required to make a 100-inch telescope lens. Glass of lower

grades is used for tableware, high-grade containers, plate glass (rolled and polished), window glass, bottles of all types, common tableware, green glass, and amber glass. Many industries make use of glass. Some of these are the drug, canning and preserving, dairying, electrical, building, and automobile industries.

ENGINE SAND

It is rather surprising to learn that nearly 2,500,000 tons of sand is used annually in this country by the railway industry. The sand is used to prevent the slipping of the drive wheels of locomotives. The chief prerequisites of an engine sand are that its grains be fairly uniform in size; that it be free from lumps of any kind that would choke the pipes leading to the wheels; and that it be free from any material that would absorb moisture. Most railroad companies select their engine sand with care. All the sand grains should pass through a 20-mesh and be retained on an 80-mesh screen. Engine sand is produced in 40 states, especially *Pennsylvania, California, West Virginia, Indiana, Kansas, and Ohio*.

FIRE OR FURNACE SAND

Furnace sand (with a little lime or fire-clay binder) is used for lining and patching furnaces, converters, ladles, cupolas, and other vessels that are to contain molten metals. The requirements are those of a good steel-molding sand.

FILTER SAND

Filter sand is used for filtering municipal water supplies. It must be free from clay, organic matter, and flat particles. The sand grains must be of fairly uniform size. The so-called "effective sizes" used in filter-sand specifications range from 0.20 to 0.70 millimeter in diameter. Uniformity is expressed by a coefficient which is the ratio of the size of grain (at least 60 per cent must be finer) to the effective size. This coefficient ranges from 1.25 to 1.80. Sands having angular or rounded grains may be used. The St. Peter sandstone of *Ottawa, Illinois*, is used as a filter sand. Only 16 states make a production of filter sand, and *New Jersey* produces nearly half of the total amount.

POTTERS' SAND

Potters place sand upon the floor of their kilns between the saggars and between the heavier grades of pottery to prevent their adhering to one another. Both fine and coarse sands are used, depending upon the kind of ware. Sand from 10 to 40 mesh is considered coarse, and 30 to 100 mesh is fine. The sand must be free from clay and iron impurities, unless the character of the ware renders this unnecessary.

STANDARD SAND

Standard sand is used in cement- and mortar-testing laboratories. The sand grains must be of perfectly uniform size and shape in order to give comparable results. The St. Peter sand is well adapted to this use.

SAND FOR CHEMICAL USES

Some sand is utilized in making certain products requiring silica. An especially common product is the colloidal sodium silicate or water glass. Sand is one of the principal constituents of the artificial abrasive carborundum, but this will be discussed under Abrasives. Sand is used in the electrolytic manufacture of ferrosilicon. For these chemical purposes, it must be a very pure quartz sand, and the grains must be of uniform size.

GROUND SAND

There are numerous miscellaneous uses for finely ground quartz (also called "silica"). Sandstone is the most common source of this quartz; it constituted 90 per cent of it in the United States in 1927. The remainder is made from vein quartz, pegmatites, and quartzite. The sand or quartz used for this purpose must have the same degree of purity as glass sand; hence a considerable amount of fine sand left from screening glass sand is used for grinding. Size of grain of the sandstone or other quartz material is unimportant, as all of the material is ground up.

The vein quartz for grinding may be obtained from pure quartz veins, but much of the quartz occurring in pegmatites that is used for this purpose is obtained as a by-product from feldspar mining. Quartzite, if pure, is satisfactory for grinding. A quartzite quarried near Wausau, Marathon County, Wisconsin, is 99.07 per cent silica.

Sandstones used for grinding are produced in *Illinois, Missouri, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin*. A number of states produce the quartz obtained from veins, pegmatites, and quartzites. The leading states in 1926 were *California, Maryland, Nevada, New York, and North Carolina*. Six or seven more made small productions.

Uses of Ground Sand.—For most purposes, the grains of the ground sand or quartz should pass through a 350-mesh screen, though for some uses a coarser product is possible. The uses of ground sand are many. It is mixed with clay to reduce the shrinkage of clay products during firing and is also employed as a constituent of pottery glazes. It is used as a paint filler, a wood filler, and a scouring agent; for frosting glass; in making fine sandpaper, sand belts, soaps, and polishes; as a cleaner by dentists; in making tooth pastes, cosmetics, and filters; as a foundry-mold wash or parting; and in making stucco, wall board, and special plasters. Some coarse quartz is used for filters in acid towers, as a flux in copper smelting, and as grit for poultry.

Selected Readings on Sand and Gravel

- DAKE, C. L.: The Sand and Gravel Resources of Missouri, Mo. Bur. Geol. and Mines, vol. XV, 1918.
- LADDO, R. B.: "Non-Metallic Minerals," pp. 499-515, McGraw-Hill Book Company, Inc., New York, 1925.
- RIES, H.: Molding Sand, Geol. Survey Committee Am. Foundrymen's Assoc. *Rept.*, 1925.
- : The Use of Standard Tests of Molding Sands, Am. Inst. Min. and Met. Eng. *Trans.* 1552-H, February, 1926.
- SHAW, EDMUND: Washing and Sizing Sand and Gravel, Am. Inst. Min. and Met. Eng. *Trans.* 1568-H, February, 1926.
- WEIGEL, W. M.: Technology and Uses of Silica and Sand, U. S. Bur. Mines *Bull.* 266, 1927. This is an excellent paper on sand.
- : Preparation and Use of Industrial Special Sands, Am. Inst. Min. and Met. Eng. *Trans.* 1569-H, February, 1926.

Selected Readings on Glass Sand

- BOSWELL, P. G. H.: "British Resources of Sands," London, 1916.
- FETTKE, C. R.: American Glass Sands, Their Properties and Preparation, Am. Inst. Min. and Met. Eng. *Trans.* 1531-H, February, 1926.
- HODKIN and COUSEN: "A Textbook of Glass Technology," London, 1916.

GYPSUM

The softness of massive gypsum (alabaster) makes it easy to work into any desired shape, and consequently it has been used by man for a very long time.

Early History of Gypsum.—Both the Assyrians and the Egyptians used gypsum for making vessels and boxes and for sculptural purposes. Five or six thousand years ago, the Egyptians made plaster from calcined gypsum and used it in the construction of the pyramids. Although this plaster is reported as being hard and durable today, its durability is apparently a matter of climate, for a recent examination of a piece of mortar from Khufu pyramid (built by Cheops) showed it to be really a weak mortar containing more uncalcined alabaster than plaster of Paris. The same material in the moist climate of the United States would have disintegrated long ago.

The Greeks apparently made use of calcined gypsum and of lime. Very likely, the use of the gypsum came about accidentally through an attempt to convert it into lime, as limestone and gypsum are very similar rocks save for hardness. It is of interest to note that the tools used by these ancient peoples were similar to those used today.

The Romans apparently employed more lime than gypsum for plasters. They built their walls and then produced a smooth inner surface by building up the irregularities with mortar. The writer of this book measured thicknesses of plaster of more than 4 inches on some of the walls in the Roman Forum.

White alabaster has been used for building purposes in Europe for many centuries, and the calcined product to a very limited extent for plaster and for making casts.

History of Gypsum in the United States.—The use of gypsum in the United States goes back over a century. Its occurrence in New York

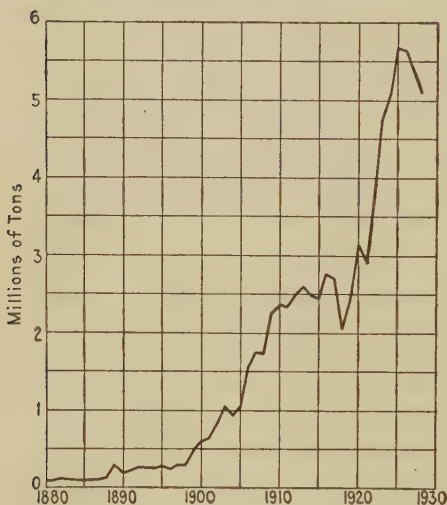


FIG. 213.—Curve showing the production of gypsum in the United States from 1880 to 1928. (*U. S. Mineral Resources.*)

was first reported in 1792, and attempts were made to quarry it for land plaster in 1808. The first reported production, however, was in 1892, 100 years after its discovery. The discovery of gypsum in other states was as follows: Virginia in 1835, Michigan (at Grand Rapids) in 1840, Ohio (at Sandusky) before 1850, Iowa in 1872, and California in 1875. The curve in Fig. 213 shows the production in the United States from 1880 to 1928. The use of calcined gypsum as wall plaster began in the early nineties and greatly stimulated gypsum production. Such recent inventions as wall board and gypsum tile have been a further stimulus.

Composition of Gypsum.—Gypsum is a hydrous sulfate of lime, having the formula $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. This formula requires 32.6 per cent CaO ; 46.5 per cent SO_3 ; and 20.9 per cent H_2O . The workable deposits of gypsum are, however, rarely if ever pure. They contain silica, iron oxides, alumina, and calcium and magnesium carbonates (see Fig. 214).

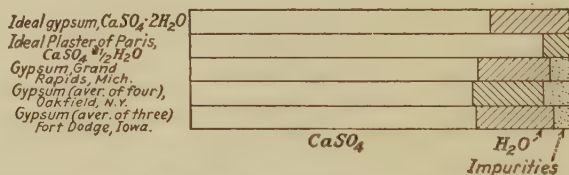


FIG. 214.—Graph illustrating the composition of various gypsums and of ideal gypsum and plaster of Paris. (*Data, in part, from U. S. Geol. Survey Bull. 697.*)

The fine, earthy variety which is deposited by springs and known as "gypsite" may contain more than 10 per cent impurities.

Physical Properties of Gypsum.—Gypsum is a soft rock, being easily scratched by the finger nail. It is more or less porous. This permits the entrance of water in which it is slowly soluble. As a result, thick

beds of gypsum commonly contain solution channels and caverns. The color of gypsum is usually gray or dirty white but may be pink, red, yellow, brown, or nearly black.

Varieties of Gypsum.—Gypsum occurs in three forms: a massive form, *alabaster*; a form occurring in crystals which split into thin sheets, *selenite* (erroneously called “isinglass” or “mica”); and a fibrous form, *satén spar*. The last two do not occur in sufficient abundance to be of much use commercially, but they are of interest as mineralogical and museum material. The massive gypsum and gypsite are the varieties used in most gypsum plants.

Mode of Occurrence of Gypsum.—Massive gypsum occurs in beds from a fraction of a foot to more than 1,400 feet in thickness. It is interbedded with shales, sandstones, dolomites, and limestone. Large deposits of salt occur with gypsum; and, in some districts, anhydrite, the anhydrous calcium sulfate, CaSO_4 , is associated with it. In eastern New Mexico and western Texas, potash occurs with gypsum.

Origin of Gypsum.—Ground waters transport calcium sulfate and redeposit it wherever the conditions are suitable. Thus, crystals of selenite are found in many kinds of rocks, but especially in clay and shale. Streams carry calcium sulfate to the sea, where it accumulates. Where a body of sea water is cut off from the sea and evaporation has brought about sufficient concentration, gypsum is deposited (see p. 551). Likewise, in an inland body of water in which evaporation exceeds the influx of water, gypsum might eventually be deposited. According to Branson,¹ gypsum may have been deposited in a series of lakes under the following conditions: some evaporation occurred in the first lake, from which the water flowed to the next; more concentration took place in the second lake; and the final deposition occurred in the last lake under sediment-free conditions. This theory would account for the pure beds of gypsum which occur and also for the thick beds (due to the concentrated solutions in the last lake of the chain).

If evaporation continues in a body of water after the gypsum has been deposited, salt will finally be deposited. It has been shown that in very salty water, anhydrite is deposited rather than gypsum. Some men believe that gypsum is derived, in part at least, from anhydrite by the addition of 2 parts of water. This may be the true origin of some gypsum deposits, but it is not true for all. Where gypsum occurs in beds unassociated with anhydrite, as it does in the immense deposits in the Rocky Mountain region and elsewhere, it is very probable that it was deposited originally as gypsum. Deposits of anhydrite unassociated with gypsum should be regarded as original. Where the two rocks are associated, each may have been derived from the other, but usually the gypsum is second-

¹ BRANSON, E. B., *Origin of Thick Salt and Gypsum Deposits*, Geol. Soc. Am. Bull., vol. XXVI, pp. 231–242, 1915.

ary. Gypsum occurs in much greater abundance than anhydrite, which favors the view that it is the more common form deposited.

Geologic Distribution of Gypsum in the United States.—Gypsum is found in the rocks of all ages since and including the Silurian. This widespread geologic distribution is shown by the following table, which gives, also, the geographic distribution of gypsum in the United States:

TABLE 101.—THE GEOLOGIC AND GEOGRAPHIC DISTRIBUTION OF GYPSUM IN THE UNITED STATES

Period	States
Pleistocene.....	Kansas, Oklahoma, Texas, Wyoming, Arizona, New Mexico
Tertiary.....	California, Nevada
Cretaceous.....	Arkansas
Jurassic.....	Utah, Colorado, Montana, New Mexico
Triassic.....	South Dakota, Nevada, Wyoming, Montana
Permian.....	Colorado, Iowa, Kansas, Arizona, Oklahoma, Texas, New Mexico
Pennsylvanian....	Montana, Nevada, New Mexico, Arizona
Mississippian.....	Michigan, Virginia, Iowa
Silurian.....	New York, Ohio, Michigan, northern Pennsylvania

The gypsum deposits in the eastern part of the United States are dominantly Silurian in age.

The most extensive deposits in this country, however, are those in the western part. They are found in the Pennsylvanian, Permian, Triassic, and Jurassic formations. The sandstones and shales associated with the gypsum deposits are dominantly red so are known as the "red beds."

Gypsum Deposits of the United States.—The chief states in which *gypsum* is found are *New York, Iowa, Michigan, Texas, Ohio, Nevada, and Oklahoma*. The accompanying map (Fig. 215) shows the location of the most important gypsum deposits, the principal producing areas, and the location of the mills using domestic gypsum. *Anhydrite* occurs in the following states: *Virginia, Michigan, Oklahoma, New Mexico, Texas, and Louisiana*. The amount of gypsum available in the United States is enormous, far in excess of any demand for gypsum products.

Gypsum of Eastern United States.—The gypsum in New York occurs in lenticular beds, 4 to 10 feet thick. The deposits of Iowa are from 3 to 30 feet thick and are overlain by glacial drift. The gypsum in Michigan is very pure. The beds near Grand Rapids, Michigan, are from 6 to 12 feet thick; those near Alabaster in the northeastern part of the state are about 23 feet thick. The composition of the gypsum of these three states is shown graphically in Fig. 214.

Gypsum of Western United States.—The thickness of the gypsum beds throughout the western part of the United States is variable. In some states, the material used is largely gypsite (which always occurs as small thin deposits on the surface); in others, beds from 4 to 30 feet

thick form the chief source; and in a few places, active quarrying is being carried on from beds 200 or 300 feet thick. R. W. Stone estimates that the total length of the outcrop of the "red beds" (Chugwater) containing a gypsum bed at least 4 feet thick (thicknesses of 100 feet are attained and average is about 20 feet) is over 800 miles. A well east of Carlsbad, New Mexico, showed 1,325 feet of gypsum (anhydrite), which is a truly remarkable thickness¹ (see Fig. 227, p. 548). A still greater thickness has been reported for the Castile gypsum member of the Guadalupe group in Eddy County, New Mexico.²

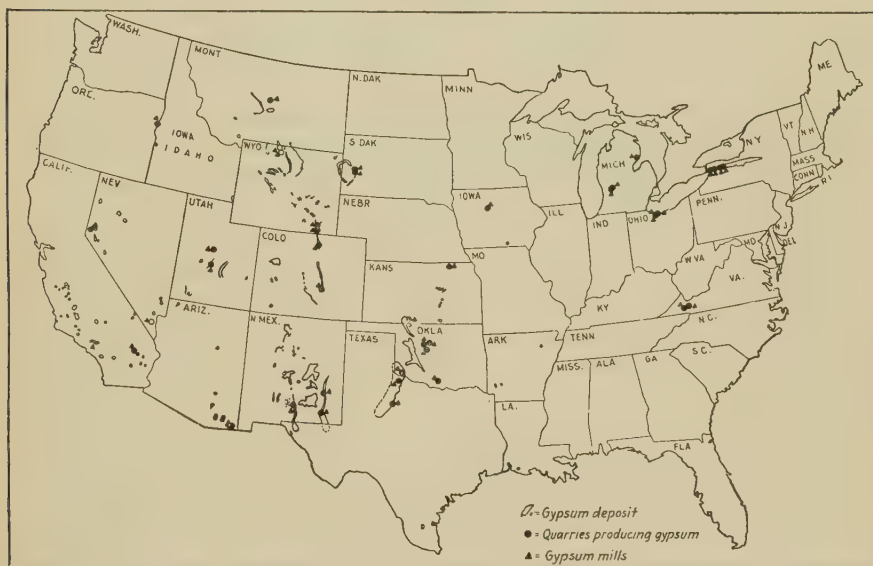


FIG. 215.—Map showing the distribution of the important gypsum deposits in the United States, and the location of the producing quarries and gypsum mills. (Data from all available sources.)

In some states, such as Kansas, Oklahoma, Texas, and parts of some of the Rocky Mountain states, the beds are nearly flat; in other areas, the gypsum formations dip at various angles. As gypsum deposits are so widely scattered throughout the west, it is to be expected that gypsum-plaster mills would be well distributed (see map, Fig. 215).

Preparation of Gypsum for Use.—Though some gypsum is used in the raw state, the greater part of it is first calcined or heated to drive off water. By heating gypsum to a temperature between 176°C. (350°F.) and 198°C., three-fourths of the water is driven off. The reaction is as follows:



¹ DARTON, N. H., U. S., Geol. Survey *Bull.* 697, p. 176.

² DARTON and REESIDE, *G. S. A. Bull.*, vol. XXXVII, p. 420, 1926.

The resulting product is called "calcined gypsum" or "plaster of Paris." Calcined gypsum has the property of taking up water again and changing back to gypsum, which causes the setting of the plaster.

The Manufacture of Calcined Gypsum.—The process of calcining gypsum is relatively simple. When rock gypsum is used, it has to be crushed, dried, and reground. Gypsite is fine enough to be calcined without previous treatment. The powdered gypsum is placed in large steam-heated kettles, 8 to 14 feet in diameter (rotary kilns are used in some mills), and the temperature raised slowly to 176°C. Care must be taken not to exceed 205°C. (400°F.), as all the water would then be driven off and the product would not have the necessary setting properties. The calcined product is drawn off from the kettles, screened, and put in cooling bins. The product at this stage would set in from 6 to 8 minutes, so a retarder is added the amount of which varies with the length of time it is desired to keep the material from setting. Retarders may be organic materials, such as hair, glue, molasses, ground peas and beans, sawdust, and fiber; or inorganic materials, such as lime, caustic soda, and slag. One of the most common retarders is a specially prepared glue of which only 0.25 per cent is required to retard hardening for about 2 hours. Gypsite is extensively used for making hard wall plaster or cement plaster, because it contains more or less foreign material which retards the setting sufficiently without the addition of other retarders.

Gypsum neat plaster (the chief product for the plastering trade) contains about one-sixth of its weight of hydrated lime, which improves its plasticity and retards its setting for about 2 hours.

Uses of Gypsum.—As has been said, gypsum is used in the raw state and as the calcined product. Of the gypsum production in the United States in 1927, 82 per cent was calcined before use.

Uses of Raw Gypsum.—The major use of raw gypsum in the United States is as a retarder in Portland cement, 928,000 tons (or 96 per cent) being used for that purpose in 1927. Its use as land plaster or fertilizer accounted for 29,000 tons. Gypsum is not in itself a plant food, but it reacts with other substances to set free plant foods. It is believed to be good for crops of clover, alfalfa, and other legumes. By converting the carbonates of sodium and potassium (which are called "black alkali" in some western states) into the sulfates, it produces substances which are less harmful to plants. Ground gypsum is also used on manure piles, where the sulfate radical unites with escaping ammonia to form ammonium sulfate, a valuable plant food. A small quantity of raw ground gypsum is used in paints; in the common wall tints used by mixing with water; as a filter for all kinds of paper, especially the better grades; as a filler for cotton; for blackboard crayons; as a base for Paris green and other insecticides; in imitation meerschaum and ivory; and as an adulterant.

Unground gypsum may be used as a building stone, as a road material, and for making statuary and other decorative objects. Very little is employed for sculptural uses in the United States. The translucent variety of gypsum is used for making jewelry boxes and powder boxes. The ancients prized it highly for these purposes.

Uses of Calcined Gypsum.—Calcined gypsum has the property of setting or hardening quickly so has a wide variety of uses. Most of it is used as various plasters, such as cement plaster, stucco, plaster of Paris, sanded plaster, neat plaster, floor plaster, Keenes cement, and finishing plaster.

The next most important use of the calcined gypsum is in the manufacture of plaster board or wall board, partition tile, and special tile and blocks.

Plaster board is made by pressing two or four layers of paper, felt, or thin wood with one or three layers of plaster between. It is made in sheets, 32 by 36 inches, which are from $\frac{1}{4}$ to $\frac{1}{2}$ inch thick. This board has many uses among which are those for fireproofing, sheathing, and sound deadening.

Partition tile, which are light and of the highest type of fireproofing, are used extensively for partitions, floors, roofs, and furring. They are usually plastered with gypsum wall plaster. Their sizes are usually 12 inches in width, 2 to 8 inches thick, and 24 to 30 inches long. Floor tile are 19 by 30 and 7, 9, 11, or 13 inches thick.

Still other uses of calcined gypsum are for embedding plate glass, granite, and marble during polishing; for making relief maps and models; and for making molds for rubber stamps, pottery, terra cotta, and special castings. Many special cements are made from it, notably dental cement. It is used in statuary and other art work and in relief decorations on walls and ceilings. Some is used in asbestos pipe coverings and in the material on match heads. High-grade plaster of Paris is used in making bandages for plaster casts.

Selected Readings on Gypsum

- ADAMS, G. I., and others: Gypsum Deposits of the United States, U. S. Geol. Survey *Bull.* 223, 1904.
- ECKEL, E. C.: "Cements, Limes, and Plasters," John Wiley & Sons, Inc., New York, 1907.
- LADOO, R. B.: "Non-metallic Minerals," pp. 281-299, McGraw-Hill Book Company, Inc., New York, 1925.
- RIES, H.: "Economic Geology," pp. 244-259, John Wiley & Sons, Inc., New York, 1925. Contains good bibliography.
- STONE, R. W.: Gypsum Products, Their Preparation and Use, U. S. Bur. Mines *Tech. Paper* 155, 1917.
- and others: Gypsum Deposits of the United States, U. S. Geol. Survey *Bull.* 697, 1920. Contains good bibliography.
- U. S. Mineral Resources* contains much interesting material in addition to production figures.

LIME

Although some ancient races (the Incas, for example) used no binding materials in building, the majority of them employed some sort of mortar. This was usually made of lime. The discovery of the method of making lime was probably an accident, such as pieces of limestone used near a fire becoming burned on the exterior and slaking when water was spilled upon them. The use of lime dates back at least 6,000 or 8,000 years. In spite of the recent enormous increase in the use of Portland cement and the increased use of gypsum wall plaster, the production of lime in the United States has remained about 4,000,000 short tons annually (see Fig. 216).

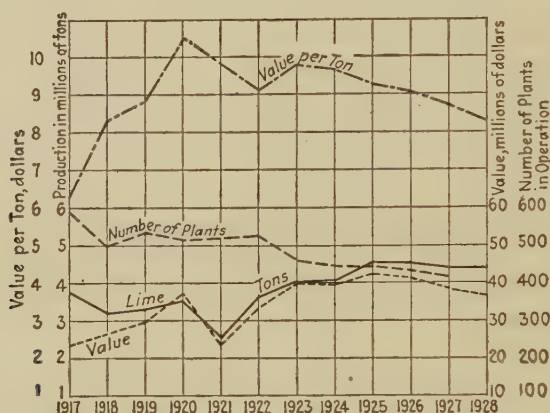


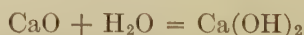
FIG. 216.—Curves showing the production of lime, its value, its average value per ton, and the number of plants in operation in the United States from 1917 to 1928. (Data from *U. S. Mineral Resources*.)

Manufacture of Lime.—Lime is calcium oxide, CaO . It is obtained by heating limestone (composed essentially of calcite, CaCO_3) to a minimum temperature of 903°C ., which drives off the carbon dioxide and leaves the lime:



The “burning” of the limestone is accomplished in various types of kilns, of which the vertical one is the most common. Ruins of old-fashioned lime kilns are to be seen throughout the United States, for much of the lime used in the past was made locally wherever limestone was available.

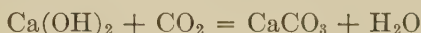
When water is added to lime, it slakes, *i.e.*, takes up water and forms hydrated lime:



About 32 per cent of water is necessary for this reaction. During recent years, a constantly increasing quantity of hydrated lime has been pro-

duced by the lime manufacturers. Hydrated lime is easier to ship (it can be shipped in paper bags), is safer to store (if unslaked lime becomes wet, it may develop sufficient heat to set fire to a building), and has greater strength than the unslaked lime. Of the lime produced in 1927 in the United States, 36 per cent was hydrated.

After being mixed with sand, the hydrated lime is called "mortar" or "plaster." Though mortar has a wide range of uses, its chief one is for plastering walls. "Plaster" is defined by the U. S. Bureau of Standards as any dry material which when mixed with water makes a plastic mass that hardens when placed on an interior surface. Thus, plaster would include not only lime mortar but also gypsum wall plaster and even Portland cement. Mortar hardens on a wall, first by losing water, and then by slowly absorbing carbon dioxide from the air and changing back to CaCO_3 :



This last change requires a long time, usually hundreds of years.

Dolomite may be used in the manufacture of lime, and if so the lime is a magnesian one. Limes which contain over 90 per cent CaO are known as "hot," "quick," or "fat" limes. They slake rapidly, develop considerable heat in the process, increase in volume about three times, and set rapidly. Magnesian limes contain over 30 per cent MgO and are known as "cool" or "slow" limes because they slake slowly.

Distribution of Lime Manufacture in the United States.—The wide distribution of limestone in the United States has been commented on and is shown by the map of the limestone areas (Fig. 202, p. 484). The manufacture of lime in 41 states is in keeping with this wide distribution of the source rock limestone. The geological age of limestone is of no

TABLE 102.—AMOUNT AND VALUE (ESTIMATED) OF THE LIME PRODUCED IN 11 STATES, 1928¹

State	Amount, short tons	Value
Ohio.....	1,015,000	\$8,982,000
Pennsylvania.....	800,000	6,000,000
Missouri.....	301,000	2,263,000
West Virginia.....	285,000	1,763,000
Alabama.....	193,000	1,441,000
Tennessee.....	181,000	1,113,000
Virginia.....	167,000	1,189,000
Wisconsin.....	164,000	1,245,000
Massachusetts.....	163,000	1,954,000
Maine.....	122,000	1,240,000
Michigan.....	110,000	1,008,000

¹ U. S. Mineral Resources, 1928.

significance in its use for making lime; accessibility for quarrying, purity, and a source of cheap fuel are the conditions to be considered. No less than 11 states are estimated to have produced over a million dollars worth of lime in 1928. This estimated production and its value are given in Table 102.

TABLE 103.—CHEMICAL USES OF THE 1926 LIME PRODUCTION IN THE UNITED STATES
(C = calcium lime, M = Magnesian lime, Mg = magnesite)

Use	Type of lime	Amount, tons	Value
Bleaching industry:			
Manufacture of bleaching powder, CaCl_2	C	5,864	\$ 46,735
Bleaching liquids for rags, jute, paper.....	C, M	9,581	99,218
Caustic alkali industry:			
Manufacture of soda, potash, ammonia.....	C	26,549	203,692
Chemical manufacture of:			
Calcium acetate.....	C	7,128	56,665
Alcohol.....	C	3,295	28,150
Mercury.....	C	22,285	177,100
Coke and gas manufacture (gas purification and plant by-products)	C, M	26,678	200,614
Creameries and dairies.....	?	2,719	43,427
Disinfectants and deodorizers (chloride of lime, etc.).....	C	5,432	42,875
Flour mills (clarifying grain).....	C, M	527	5,275
Glass works.....	C, (M)	84,263	713,321
Glue.....	C, M	11,120	92,771
Insecticides and fungicides (spraying materials).....	C, M	14,558	141,108
Metallurgy (smelting various metals).....	C, M	408,234	2,860,338
Oil and fat manufacture.....	C	4,809	44,984
Paint (calcimine, whitewash, varnish, linoleum, linseed oil).....	C, M	2,156	20,355
Paper mills.....	C, M, Mg	423,322	3,492,996
Pottery and glazing.....	C		
Refractory lime (dead-burned dolomite).....	C, M	386,715	3,593,731
Rubber.....	C, M	3,542	39,727
Salt refining.....	C	1,722	14,241
Sand-lime and slag brick.....	C, M	39,821	388,166
Sanitation (sewage and garbage purification, etc.).....	C	2,731	23,328
Silica brick.....	C, M	14,881	123,207
Soap.....	C	15,906	107,390
Sugar refineries.....	C	15,379	238,188
Tanneries, cowhides (others—C, M).....	C	66,538	584,296
Textiles.....	C, M	1,133	11,869
Water purification and softening.....	C	139,478	1,185,670
Wood distillation.....	?	12,225	101,740
Undistributed (see list below) ²		43,580	342,679
Unspecified.....		140,896	1,162,320
Total.....		1,943,065	16,186,185

¹ Data from *U. S. Mineral Resources*, 1913 and 1926.

² Minor chemical uses of lime:

Acid neutralization and drying.	Fertilizer filler.
Artificial silk.	Food products.
Asphalt and clay filler.	Gelatin (edible).
Baking powder.	Oil refining.
Buffing compounds.	Oxygen purification.
Corn products.	Poultry food.
Cyanide manufacture.	Proprietary medicines.
Dyes.	Sheep dip.
Explosives.	Tobacco.

Uses of Lime.—Few materials have a wider range of uses than has lime. These uses can be divided into three major groups, in the order of their importance: *building*, *chemical*, and *agricultural*. The use of lime in these three major groups has been essentially the same in the United States for a period of years. Building construction utilized 48.7 per cent; the chemical industries, 44 per cent; and agriculture, 7.3 per cent of the 1927 production.

Building Uses.—The chief use of lime is in the building trade. Here it is used chiefly as plaster, both for the first and for the finishing coats.

Chemical Uses.—The chemical uses of lime are widely distributed throughout the industrial field. Table 103 gives the most important of them.

Some processes require a very pure, high-grade calcium lime; in others, either a calcium or a magnesian lime may be used. In making magnesium compounds and in the sulfite method of making paper, a high-grade magnesian lime is employed. Refractory lime requires the use of dolomite for its manufacture. This lime will be discussed more fully under Refractories.

Space does not permit of a discussion of each of these chemical uses. It is of interest to note that both limestone and lime are employed in making glass. In the United States in 1927, 247,210 tons of limestone, valued at \$420,415 was so used and 78,994 tons of lime, valued at \$655,026. The mixture for the plate-glass batch has 25 per cent (by weight) calcium carbonate; the window-glass batch, 40 per cent; and the green bottle-glass batch, 33 per cent.

Agricultural Uses.—Lime for agricultural purposes will be discussed under Fertilizers.

Selected Readings on Lime

BURCHARD and EMLEY: The Source, Manufacture, and Use of Lime, *U. S. Mineral Resources*, 1913, Part 2, pp. 1509-1593. An excellent account of the entire process.

ECKEL, E. C.: "Cements, Limes, and Plasters," John Wiley & Sons, Inc., New York, 1907. Discusses the materials, their properties, and manufacture.

U. S. Mineral Resources and some state reports have material of interest.

MINERAL PAINTS

The use of various colored earthy materials mixed with some binding substance to produce a material that would spread over a surface has long been known to man. Drawings done in colors are found on the walls of the caverns occupied by men of the stone ages. Their colors were those of the common iron oxides. Primitive races of men in all parts of the earth have used these materials for coloring. A vast distance in experience and knowledge of the technique of colors separates the artists of the recent centuries from the polychrome artist of the stone ages, yet

the modern colorist uses many adaptations of the early-used materials, though adding, of course, many new ones.

At the beginning of the present century, natural pigments were still extensively employed in paints, and there was a considerable demand for ochers, umbers, and hematite for this purpose. Slowly but surely, however, materials that were more durable and better adapted to mixing have been taking the place of these simpler natural substances. In 1915, the U. S. Geological Survey found that it was no longer worthwhile to collect, for the annual volume on mineral resources, the limited statistics regarding natural pigments used for paints. Today, the only item so entered is that of the iron ore sold for paint, which, in 1927, amounted to 25,000 tons, worth \$132,000.

In spite of this low production of natural pigments, the United States is probably a greater consumer of paints than any other nation. The reason for this is, as has already been mentioned, our extensive (and unparalleled) use of wood for building construction. Wood must be protected by paints. Of course, not all the paint used in the United States is put on wood, for much is used on interior walls; but by far the greater amount is so used. The value of paint pigments sold by producers in the United States has averaged about \$25,000,000 annually for the last 10 years, but our paint bill in 1927 and 1928 was nearly \$100,000,000 each year. Structures built of brick, stone, and stucco would greatly reduce this bill, in addition to the saving that would accrue from the added length of life of the buildings.

KINDS OF MINERAL PAINTS

Mineral paints may be divided into two groups: (1) those made from *manufactured pigments*, such as lead and zinc, and (2) those made from *natural pigments*, such as hematite and limonite.

Manufactured Pigments.—The manufactured pigments are made from *lead, zinc, barium, titanium, carbon*, and a few other elements. The manufacture of lead, zinc, and barium pigments is the outstanding feature of the paint industry.

Lead and Zinc Pigments.—Lead and zinc pigments are manufactured by smelting and by chemical processes. White lead (basic lead carbonate) is made by a chemical process. Sublimed lead (basic lead sulfate) and the various lead oxides used in pigments are made in oxidizing furnaces. Zinc oxide and leaded zinc oxide (zinc oxide containing more than 5 per cent lead) are made directly from the ore by sublimation. Zinc oxide manufactured by the French process is made from metallic zinc. Lithopone, which contains 30 per cent zinc sulfide, is made by a chemical process. In making lead pigments in the United States in 1925, 94 per cent of the material used was metallic lead, and the remainder was lead

ore. In making the zinc pigments, 71 per cent of the materials was zinc ore, 22 per cent was metallic zinc (used in the French process), and 7 per cent was from secondary sources. The total value of the lead and zinc pigments in 1925 was \$25,407,000, and there were similar values in 1926 and 1927.

Barium Pigments.—*Lithopone* is a brilliant white pigment made of barium sulfate (70 per cent) and zinc sulfide (30 per cent). It can be made directly from a mixed ore of sphalerite (zinc sulfide) and barite (barium sulfate), but the more common method (see Fig. 217) is to mix in proper proportions the chemically prepared zinc sulfate and barium sulfide. This brings about the simultaneous precipitation of zinc sulfide and barium sulfate. From 1 to 3 per cent zinc oxide is usually present in the pigment, depending upon the conditions of manufacture.

The growth in the use of lithopone has been phenomenal. Its production in the United States increased from less than 5,000 tons in 1906 to nearly 229,000 tons in 1928 (see Fig. 218). The country has important barite deposits (see discussion of barite, p. 577), yet 63 per cent of the 1927 production (248,000 tons) was used in making lithopone. This did not represent all the barite used in the manufacture of lithopone, however, as 200,000 tons was so used that year. The United States imported 70,000 tons in 1927.

Titanium white is a very opaque, pure white pigment containing 75 per cent BaSO_4 and 25 per cent TiO_2 . The opacity of the titanium oxide is much greater than that of either white lead or zinc oxide, and its mixture with barium sulfate produces a very fine pigment. It is made by adding to a sulfuric acid solution of titanium a pulp of finely divided barium sulfate. The mixture is then heated above the boiling point and is violently agitated, which causes the precipitation of titanium oxide on

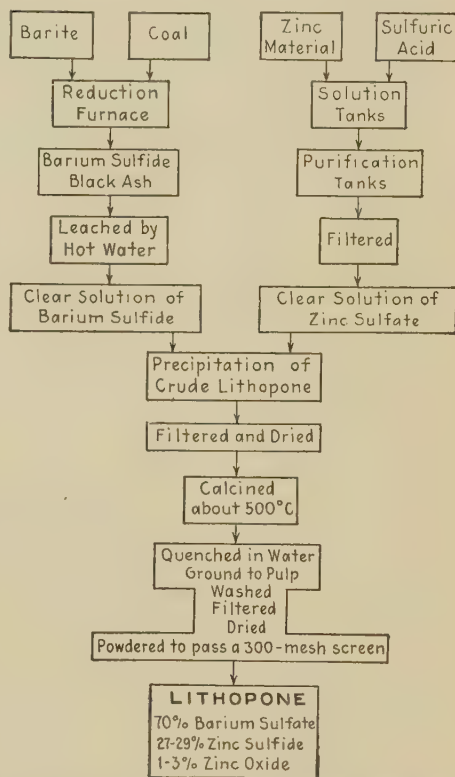


FIG. 217.—Diagram showing the raw materials used in making lithopone, and the methods of the manufacture. (Modified after Ladoo, "Non-Metallic Minerals," p. 78.)

the barium sulfate. This pigment is also known as "titanox."

Carbon Pigments.—The only carbon pigment referred to here is carbon black, which is made from natural gas as described under Natural gas. Of the domestic use of carbon black, paint companies use 10 per cent, ink companies 13 per cent, and rubber companies 70 per cent. The average automobile tire contains about 2 pounds of carbon black.

Minor Pigments.—A few other substances are used as pigments, but these can be considered only briefly here. *Venetian red* pigment is a light shade of red and is made from iron oxide and calcium sulfate; *vermilion* pigment is artificial mercuric sulfide, HgS ; *chrome red* is basic lead chromate, $\text{PbCrO}_4 \cdot \text{PbO}$; *cadmium yellow* pigment is cadmium sulfide,

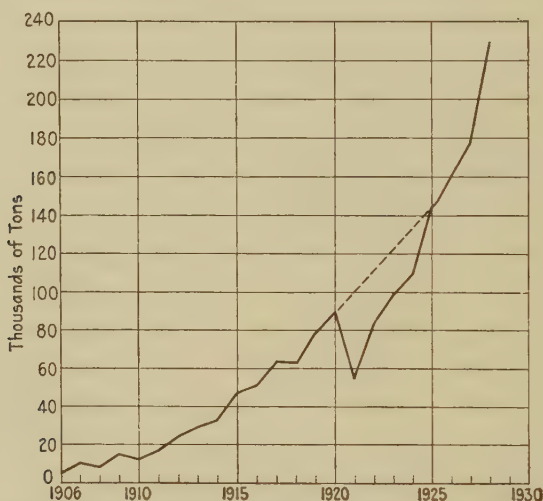


FIG. 218.—Curve showing the production of lithopone in the United States from 1906 (first year of production) to 1928. (Data from U. S. Mineral Resources.)

CdS ; *chrome yellow* pigment is lead chromate, PbCrO_4 ; *chrome green* pigment is a mixture of chrome yellow and *prussian blue*, $\text{Fe}_7\text{C}_{18}\text{N}_{18} \cdot 10\text{H}_2\text{O}$; and *cobalt blue* pigment is cobalt oxide, CoO , mixed with some silicate. These pigments require special chemical treatment in their preparation.

Natural Mineral Pigments.—The natural mineral pigments include *hematite*, *limonite*, *ocher*, *sienna*, *umber*, *slate*, *shale*, and a series of finely ground inert substances, such as *graphite* and *asbestos*, which are usually employed as fillers.

Hematite and Limonite Pigments.—The two common iron oxide minerals are the most important natural mineral pigments. After being cleaned and dried, the hematite and limonite are ground; for all paint materials must be finely ground. This grinding also aids in producing

a perfectly uniform color, which is another prerequisite of a good paint. Certain colors are produced by roasting the material and driving off all or part of the water. Soft ores are best suited for making paint. Such ores are commonly found where a bed of ore has been disintegrated by weathering or where the "paint rock" itself is residual from the weathering of some rock. Iron ores used in making paints are produced at several points in eastern United States. The Clinton iron ore of the Silurian formation is commonly so used. The limonite deposits of the southern Appalachians also contribute some material.

Ocher Pigments.—Most ochers are mixtures of iron oxides and clay. Some ochers contain as low as 15 per cent iron oxides; but others contain 80 per cent, in which case the ocher is essentially a low-grade iron ore. The same requirements of color and uniform size of particles must be met by the ochers used as paint pigments as are required of the iron oxides for such uses.

Umber is an ocher containing some manganese oxide, which gives a brown color to the substance. When the material is roasted, a deeper and richer brown color is obtained and the material is called *burnt umber*. If the manganese oxide content is small, the material will be a yellowish-brown color and is known as *sienna*. With roasting, the color becomes a real brown.

Ochers are of widespread occurrence, but the deposits are usually small and scattered. Ocher deposits are usually residual from the weathering of almost any type of iron-bearing rock.

Georgia, Pennsylvania, and numerous other states are sources of these materials in the United States. The best grades of ocher bring \$10 to \$12 a ton.

Miscellaneous Substances.—Only small amounts of other natural substances are utilized in paints. Some *barite* is employed with white lead to make paint, and both *slate* and *shale* are ground fine and so used. Colored slates and shales are analogous to low-grade ochers. Pure calcium carbonate is utilized in paints and is known as *whiting*. Chalk is the best natural source of it, but it can be made from some limestones. The precipitated calcium carbonate, however, is finer and better. *Graphite* is used in paints which are to cover iron and steel. *Asbestos* is employed in fireproof paints. Powdered *quartz* is used to a limited extent. *Vermiculite*, a mineral formed by the alteration of mica, is a recent addition to the materials used in paints. *Talc* is used as a pigment and filler in waterproof and roofing paints.

Selected Readings on Mineral Paints

LADOO, R. B.: "Non-Metallic Minerals," pp. 368-391, McGraw-Hill Book Company, Inc., New York, 1925. This contains the best article on mineral pigments in recent literature. A very good bibliography is given.

ASPHALT

Asphalt is the most common of the several solid or semisolid members of the hydrocarbon family. An interesting classification of these substances has been built up, but it is not necessary to give it here. Asphalt and related bitumens vary considerably in composition.

Mode of Occurrence of Asphalt and Some Related Hydrocarbons.—

Natural asphalt is found on the surface as seepages some of which are small deposits and others of which are large. The asphalt lake on the island of Trinidad covers 135 acres, and the Bermudez asphalt lake in Venezuela is half a mile long and from 300 to 600 feet wide. Asphalt also occurs as a cementing material in sandstones and as scattered particles in irregular openings in other rocks.

A number of these solid hydrocarbons occur as veins or dikes and are known as *gilsonite*, *wurtzilite*, and *ozokerite*. Some of them are mineral waxes containing considerable paraffin.

Origin of Asphalt.—Asphalt is largely an oxygenated compound that has formed from crude oil through the evaporation of the lighter hydrocarbons and the partial oxygenation of the remainder. It is obtained as a residue from the distillation of many crude oils, which is evidence that the natural asphalt had a similar origin. The natural asphalt thus formed may reach the surface, accumulating as a lake or brea deposit; or it may remain in the parent rock, forming a bituminous rock.

Production of Asphalt in the United States.—Over 80 per cent of the asphalt produced in the United States is derived from the refining of asphaltic oils. These oils are largely (60 per cent) Mexican, Venezuelan, and Colombian, but some are of domestic origin. The domestic oils come from *California* and the *Texas-Louisiana* gulf fields, although some production is made from asphaltic oils of other states.

Uses of Asphalt.—Nearly 50 per cent of the solid, semisolid, and liquid asphalts sold in the United States in 1928 was used in paving; and, if road oil were included in this percentage, it would be 52 per cent. Asphalt paving includes the following types: sheet asphalt, asphaltic concrete, asphalt macadam, and asphalt-block pavements. Asphalt is also used as a joint filler in brick, block, and monolithic pavements. Bituminous rock is likewise used for paving, but not so extensively as the pure asphalt. Kentucky asphaltic rocks are sandstone, those from Texas are mainly limestone.

The next most important use of asphalt is as roofing and waterproofing material. This use accounted for over 34 per cent (about \$15,000,000 in value) of the United States production in 1928. In this use, the asphalt is largely employed in making shingles. The asphalt is used to saturate and coat a felt or other fabric, which is then covered with slate granules.

According to *Mineral Industry* for 1926,¹ 36,300,000 squares (a square covers 100 square feet) of roofing was made in the United States that year. This amount would be sufficient for 3,630,000 dwellings averaging 10 squares per building. The use of asphalt for waterproofing is also extensive.

The list of minor, yet important, uses for asphalt is a long one. The rubber industry in the United States uses annually about 25,000 tons as a cement, known as "mineral rubber." Other uses are in paints, varnishes, enamels, japans, moisture-proof wrapping paper, antiacid coatings, wall board, sheathing, flooring, pipe dips, and sealing compounds (dry cells and batteries); as a binder for briquets; and as insulating, molding, and preservative compounds. Ichthyol is an important product obtained from distilling certain bituminous shales found in Austria. It is supposed to be a type of fish oil.

Selected Readings on Asphalt

- ADAMS, G. I.: Origin of Asphalt and Related Compounds, *Am. Inst. Min. Eng. Trans.*, vol. XXXIII, p. 340, 1903.
CRUMP, M. H.: Kentucky Rock Asphalt, *Ky. Geol. Survey*, vol. I, Part 2, p. 1053, 1913.
ELDRIDGE, G. H.: Occurrence of Asphaltum and Related Hydrocarbons in the United States, *U. S. Geol. Survey 22d Ann. Rept.*, Part 1, 1901.
—: Asphalt Vein Formations, *Econ. Geol.*, vol. I, p. 437, 1906.

There are also numerous papers by the U. S. Geol. Survey, by state surveys, and in the technical journals on this subject.

ASBESTOS

"Asbestos" is a term applied to a group of minerals which possess the property of being easily separated into fibers. The word comes from the Greek word *asbestos*, meaning incombustible.

History of Asbestos.—The Romans were familiar with the use of asbestos, as they wove it into various sorts of fabrics. Charlemagne is said to have had tablecloths and napkins woven of it and to have had them cleaned after each meal by placing them in the fire. The ashes of royalty were preserved by using a cremating cloth of asbestos. Although known so long ago, the use of asbestos has not been extensive until within the last 30 or 40 years.

Physical Properties of Asbestos.—The asbestos minerals have a number of remarkable physical properties, which make possible their wide range of uses. These are: *fibrous structure, incombustibility, slow conductivity of heat, toughness and flexibility of fibers, high electrical resistance, and relative insolubility in ordinary acids.* In many industries, products are manufactured which depend for their use upon one or more of these physical properties. These properties will be considered under the discussion of each of the asbestos minerals.

¹ P. 80.

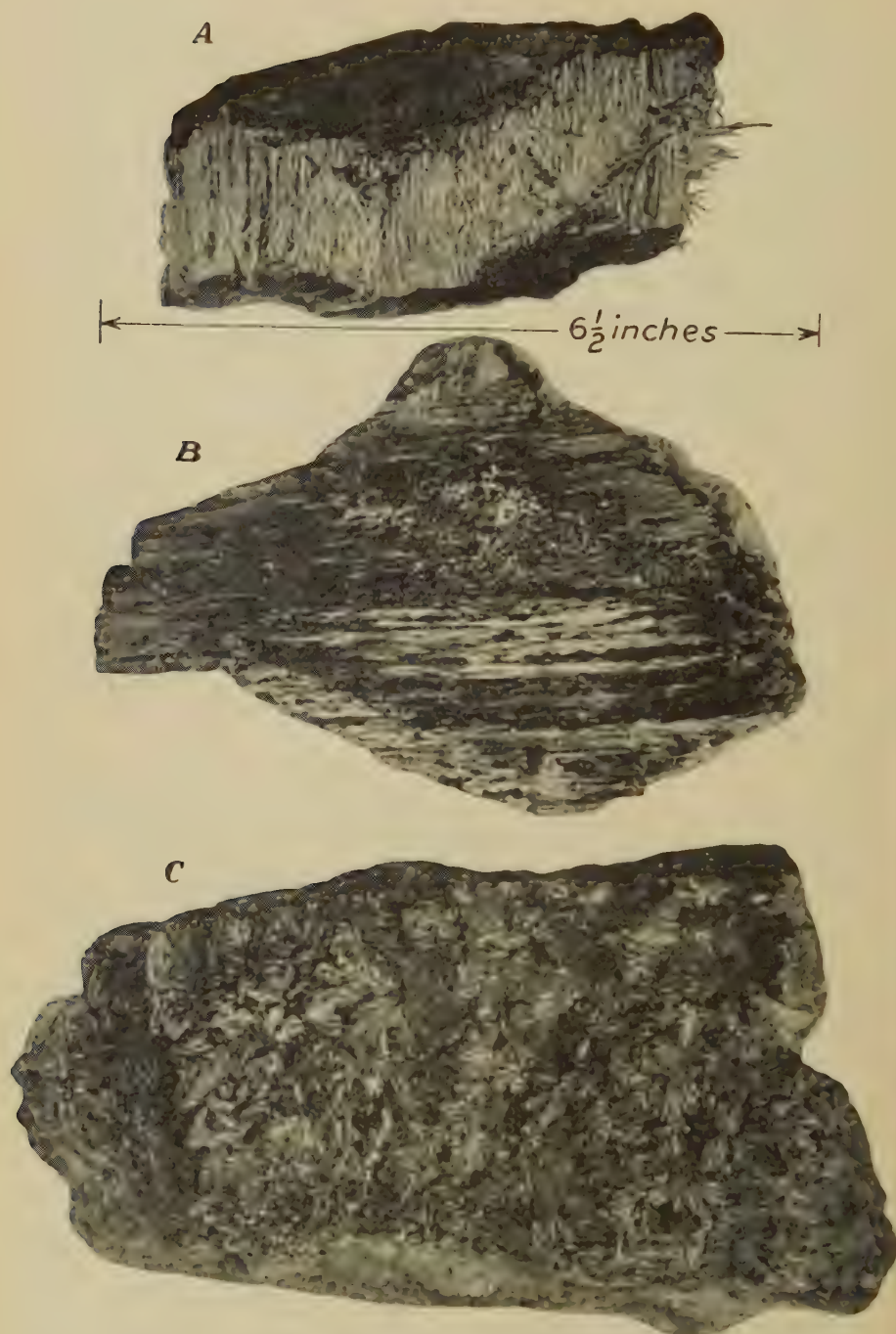


FIG. 219.—Varieties of asbestos. *A*, chrysotile (cross fiber), *B*, chrysotile (slip fiber). Both specimens from Thetford, Quebec. *C*, anthophyllite (massive fiber) from Georgia. *A* and *B*, about half size. *C*, about natural size.

Mode of Occurrence of Asbestos.—Asbestos minerals commonly occur in veins or massive. These modes of occurrence give rise to three types of fibers in the minerals. They are *cross fiber* (Fig. 219 A), *slip fiber* (Fig. 219 B), and *massive fiber* (Fig. 219 C). Where the fibers in a vein are at right angles to the vein walls, the asbestos is known as “cross-fiber” asbestos. Slip-fiber asbestos develops along fault planes or slips in the rocks. It is limited in amount. Massive fiber is, of course, the fiber of the asbestos occurring in the massive form. The fibers are coarse and are usually arranged in interlocking bunches or radially.

The Minerals Composing the Asbestos Group.—There are four or five minerals possessing fibrous structures to which the name “asbestos” is commonly applied. They are, in the order of their economic importance: *chrysotile*, $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ (a variety of serpentine); *anthophyllite*, $(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$; *crocidolite*, $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 5\text{SiO}_2$; and *actinolite*, $\text{CaO} \cdot 3(\text{Mg}, \text{Fe})\text{O} \cdot 4\text{SiO}_2$. All these minerals are members of the amphibole group; and, with the exception of crocidolite, all are magnesium silicates.

The two common asbestos minerals are chrysotile and anthophyllite (see Fig. 219 A and C). These are the only varieties produced in North America. The two minerals differ considerably in certain structural features, as will be seen from the discussion.

Chrysotile.—Chrysotile is the most important cross-fiber asbestos. It occurs as veins in serpentine, from which it separates rather easily. The fibers occur up to 3 or 4 inches in length but, for the most part, are from $\frac{1}{16}$ to $\frac{1}{2}$ inch long. In the best grades of chrysotile, they average about an inch (see Fig. 219 A).

The best chrysotile is green, has a beautiful silky luster, and, when the fibers are partially separated, has a fluffy appearance. The fibers have remarkable strength (those of a chrysotile in Arizona, when twisted into a thread 0.03 inch thick, will support an average weight of 15.5 pounds). Even more remarkable is the extreme fineness of the fibers and the ease with which they can be woven into threads. According to the U. S. Geological Survey, a thread can be spun so fine that 32,000 feet of it weighs about a pound. The Asbestos Corporation of Canada states that cloth can be woven of chrysotile thread, which will weigh less than 8 ounces to the square yard.

Anthophyllite.—Anthophyllite is various shades of gray, brown, or green. It occurs typically as mass fiber, though some occurs as slip fiber. The fibers may be arranged radially (see Fig. 219 C), or they may be bunched irregularly. Those of some anthophyllite are flexible, but in most varieties they are brittle and unsuitable for spinning into threads. They are shorter and coarser than the fibers of chrysotile and of a lower tensile strength. As a rule, anthophyllite constitutes over 95 per cent of the rock in which it occurs, whereas the mill rock in the chrysotile deposits averages about 7 to 10 per cent marketable asbestos.

An iron-rich variety of anthophyllite, *amosite*, is extensively mined in the Transvaal, Union of South Africa. Its fibers are of unusual lengths: 4 to 7 and even 11 inches.

Crocidolite.—Crocidolite, produced in Griqualand, Union of South Africa, is known as "blue asbestos." It does not have the infusibility of the other varieties but otherwise is suited for the same purposes.

Actinolite.—Actinolite is used to a limited extent as commercial asbestos. It is ground and used with other materials.

Origin of the Asbestos Minerals.—*Chrysotile* is a fibrous form of serpentine with which it is usually associated. (The deposits in Arizona are in limestone, but serpentine is present and igneous rocks are near.) Serpentine is, in most deposits, a mineral which is secondary after some olivine-rich rock, notably peridotite or dunite. The alteration of the original rock may have been due to ordinary weathering processes or to the effects of hot or warm solutions given off from intrusive masses.

The crystallization of the massive serpentine occurs along joints, where the fibers (cross fibers) grow at right angles to the walls (see Fig. 219 A). Hot solutions have undoubtedly been of aid in forming the best grades of chrysotile.

Anthophyllite is a secondary mineral usually developed in metamorphic rocks. *Crocidolite*, or blue asbestos, is also a secondary mineral. It occurs in a series of iron-rich sedimentary rocks, where the veins of cross fiber developed parallel to the bedding planes. Its origin is not clearly understood. *Actinolite* is a typical metamorphic amphibole. It develops in schists during their alteration.

Distribution of Asbestos in the United States and Canada.—The United States produces only about one-half of 1 per cent of the asbestos it needs, yet it manufactures (and uses) more asbestos products than any other country. Between \$6,000,000 and \$8,000,000 worth of asbestos has been imported annually for many years. The chief source of this raw asbestos is Canada, which furnished more than 96 per cent of our asbestos imports in 1928.

The asbestos deposits in the United States are either small and of low-grade material or are located where the cost of working and transportation is prohibitive. The most important localities where asbestos occurs in the United States and the localities of the important Canadian deposits are shown on the accompanying map (Fig. 220). Only a very small production of chrysotile is made in the United States, the major production being anthophyllite all of which comes from Georgia.

Anthophyllite Deposits.—The anthophyllite deposits of *Georgia* occur in a belt extending from Rabun County in the northeastern corner of the state to Harris County in the west-central part. Important deposits occur near Hollywood, Habersham County, and in a region 3 miles south-

west of Sall Mountain, White County. Both of these localities are in the northeastern corner of the state.

The anthophyllite is typical mass-fiber asbestos. The fibers are mostly radiating. The anthophyllite makes up most of the rock mined. The deep-seated rock is hard and much less fibrous than the weathered portion; hence, the mining is carried on from open cuts and quarries. The product sells at about \$10 per ton.

Chrysotile Deposits.—Deposits of chrysotile in the *United States* are found in northern *Vermont* at Eden, Lamoille County, and Lowell, Orleans County; near Pylesville, Harford County, *Maryland*; 20 miles

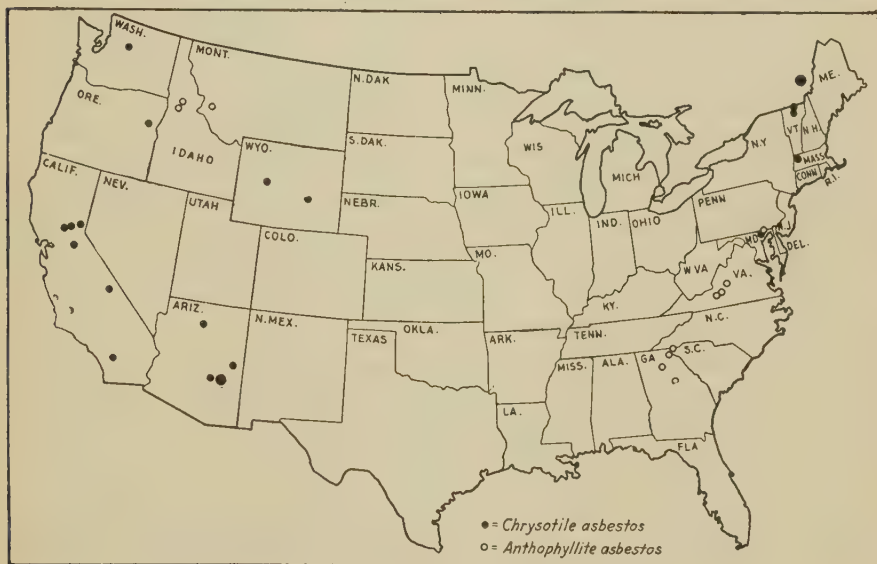


FIG. 220.—Map of United States and southern Canada showing the location of the important deposits of asbestos.

northeast of Globe in Gila County and at Grandview on the Grand Canon, *Arizona*; near Casper and in the Wind River Mountains, *Wyoming*; in *Montana*; *Washington*; *Oregon*; and in numerous other states. The material of Gila County, *Arizona*, is of very high grade, the fiber being long and of exceptional strength. The location of the deposit, however, is of difficult accessibility.

The asbestos deposits of *Canada* are located at Thetford Mines, Black Lake, and East Broughton in the province of *Quebec*. The asbestos, which is entirely chrysotile of a very high grade, occurs dominantly as the cross-fiber variety but also as slip fiber. The veins, which are in serpentine, are up to 4 inches in width.

The serpentine is the alteration product of peridotite, which was intruded along with a series of other igneous rocks into early Paleozoic sediments.

The chrysotile is quarried from open pits. The one at Thetford Mines is nearly 800 feet long, 200 feet wide, and about 200 feet deep. The rock, after being blasted down, is sorted into mill rock and dump rock. The best material in the mill rock is sorted out and commands the highest price. The other material goes to the mill, is crushed, dried, and crushed again. It then goes to screens from which it is sucked up by a current of air and after being screened again is graded and bagged for the market. The recovery from the original rock is about 6.5 per cent. The highest-grade material in 1928 was worth \$535 per ton; the next grade, \$300; spinning fiber, \$150; and the other grades, down to \$16 a ton.

USES OF ASBESTOS

The uses to which asbestos is put can be classified according to the different physical properties of the material.

Uses Based on Infusibility.—The fact that asbestos will not burn is the important property upon which is based the manufacture of fireproof materials of many types. The largest part of the asbestos produced goes into fireproof materials. A few of these products are asbestos shingles; asbestos paper for building purposes; asbestos mill board; asbestos fiber and cement; asbestos fireproof paints; asbestos felt for lining floors and walls; “asbestic,” an asbestos wall plaster; and asbestos ropes, twine, and cord for supporting weights exposed to heat. Large amounts of asbestos are also used as packing or lining for filing cabinets, safes, stoves, heaters, mufflers of automobiles, and electric switch boxes. Asbestos shingles made of asbestos and Portland cement, and asbestos roofing tile and flooring tile are in great demand. For many of these purposes, a short-fiber asbestos is used (in asbestic it is really a fibrous sand), but others, such as the felt and ropes, require a somewhat longer fiber.

Uses Based on Flexibility and Strength.—The fact that the long, fine fibers of some asbestos are tough and flexible enough to be spun and woven is made use of in making fireproof textiles and cloth. The asbestos stage curtains in theaters throughout the world are evidence of the “safety-first” use of this mineral. Much stage scenery also is made of asbestos cloth. The cloth is used for firemen’s clothes, for not only is it incombustible but it is also a non-conductor of heat. Aprons, gloves, mittens, leggings, helmets, tapes, woven sheets, packing, wicks, rope, belt conveyors, and brake linings are some of the articles woven from asbestos thread. Most of the asbestos used in making brake linings is of a very high grade, and the product is further strengthened by interweaving the asbestos threads with wire. Asbestos and rubber are extensively used in making gaskets.

Uses Based on Non-conductivity of Heat.—Asbestos is an excellent non-conductor of heat, and it is used both to retain heat in a substance

and to protect a substance from it. Various types of coverings, packings, and bulk asbestos are employed for this purpose. Steam pipes are covered with asbestos to retain the heat and to protect surrounding materials from it. Pipes in cold-storage plants are so covered to protect them from the heat where they pass through warm places. Asbestos mattresses are used around locomotives and other types of engines to retain their heat. The packing around a safe is not only for fireproofing purposes but also to protect the contents from heat. Numerous household electrical appliances contain some asbestos; such articles are table covers, table mats, stove mats, flatiron holders, and rugs.

Uses Based on Non-conductivity of Electricity.—Asbestos is a non-conductor of electricity and hence is used in the insulation of wires, switchboards, and other electrical apparatus.

Uses Based on Insolubility.—The insolubility of asbestos in most common acids permits its extensive use as filters for acids and alkaline solutions.

Miscellaneous Uses.—Asbestos fiber is used to a limited extent in paints. This use is more as a binding material than to furnish fire resistance. Garden hose, washers, gas burners, imitation leather, and even boots and shoes are made of the mineral.

Selected Readings on Asbestos

CIRKEL, FRITZ: Chrysotile Asbestos, Its Occurrence, Exploitation, Milling, and

Uses, Mines Branch, Canadian Dept. Mines, Ottawa, 1910. Very good.

MERRILL, G. P.: "Non-metallic Minerals," pp. 183-197, 1910. General account.

RIES, H.: "Economic Geology," pp. 298-309, John Wiley & Sons, Inc., New York, 1925.

The annual report on asbestos by Blanche H. Stoddard in *U. S. Mineral Resources* is a very good summary. The annual volumes of *Mineral Industry* have material on the foreign deposits.

CHAPTER XV

MATERIALS USED CHEMICALLY

INTRODUCTION

There are ten or twelve non-metallic earth materials whose uses are dominantly chemical. The character of these uses varies widely. Some materials are employed entirely in the manufacture of chemical compounds; some to bring about necessary reactions during a manufacturing process. A part of the materials are used in their raw state, and a part undergo chemical treatment to prepare them for use. Certain of these materials are utilized in a great many industrial processes, and others are restricted to a few.

Although fluctuating with industrial conditions, the annual value of the materials (not of the final products made from them) in the United States amounts to over \$85,000,000.

These materials are grouped in this chapter in order to emphasize their dominantly chemical use. Many others among the non-metallic earth materials are used in some degree for chemical purposes; but they have other more important applications, even though the method of manufacturing the product is chemical, as in the case of Portland cement.

The materials discussed in this chapter are:

Sulfur and pyrite.

Salt.

Fertilizers:

Phosphates.

Potash.

Nitrogen compounds.

Miscellaneous materials:

Sulfur.

Lime.

Glauconite.

Natural sodium compounds.

Fluorite and cryolite.

Calcium chloride, magnesium chloride, and bromine.

Barite.

Magnesite and dolomite.

Lithium minerals.

Strontium minerals.

Monazite and thorium.

SULFUR AND PYRITE

SULFUR

Sulfur (also called "brimstone") has long been used by man. Today, it is one of the essential elements in a wide variety of products and is used in practically every important manufacturing process.

The date of the first discovery of sulfur in the United States is not known, but it must have been within the last 125 years, for no important deposits are in the eastern part of the country. The Louisiana deposits were discovered in 1865 but were not worked successfully until nearly 40 years later. The Texas deposits are recent discoveries.

Physical Properties of Sulfur.—Sulfur is yellow and is so soft that it can be scratched with the finger nail. It occurs in crystal form but more often is massive. It is a non-conductor of electricity and a poor conductor of heat.

Mode of Occurrence of Sulfur.—Sulfur occurs in the native state (S) and is mined as such. It occurs, also, as sulfides in combination with other elements; and some of this sulfur, after being released from the sulfide by smelting, is saved and used in making sulfuric acid.

Sulfur is found around the craters and on the sides of most volcanoes, especially where gases are escaping. This type of deposit has long been a source of the element in Italy, Japan, Mexico, and other countries. Sulfur occurs in spring deposits along with gypsum and calcareous tufa. The chief occurrences of it are in sedimentary beds of limestone and gypsum. Various minerals, such as barite, opal, quartz, celestite, and aragonite, may be present, also. Small deposits of sulfur occur in mineral veins and in coal beds.

Origin of Sulfur.—Sulfur may be formed in several different ways, and each deposit must be studied independently to determine its origin.

In deposits associated with volcanoes, sulfur is probably due to a reaction between hydrogen sulfide, H_2S , which is escaping from the interior, and the oxygen of the air, thus:



This reaction takes place where the supply of oxygen is limited. It is common on the burning dumps of coal mines, which contain much pyrite. Other reactions, such as the breaking up of pyrite or other sulfides, also liberate sulfur.

One of the important methods by which sulfur is produced is by the action of the sulfur bacteria. During the decay of organic matter, hydrogen sulfide is given off, which may then be oxidized to sulfur by the sulfur bacteria. If produced in quantity, this sulfur might accumulate along with the enclosing rock.

A third method by which sulfur may originate is through the reduction of a sulfate. Any sulfate could be reduced; but, as gypsum is so com-

monly associated with sulfur, its reduction has been regarded as the most probable one. Certain bacteria accomplish this reduction, liberating hydrogen sulfide, which may then be oxidized to sulfur as noted above. This is the favored method of explaining the Sicilian sulfur deposits. The presence of considerable celestite and some barite is difficult to explain if the materials were all deposited on the sea floor. If anaerobic bacteria can be present in underground waters, as Bastin¹ believes, the reduction of the sulfate may have occurred after the rocks were deposited. The presence of more or less bituminous matter in the Texas and Sicilian deposits might be taken as favorable evidence for this last view.

SULFUR DEPOSITS

The United States and Sicily contain the largest sulfur deposits in the world. Until 1904, the United States imported practically all its sulfur from Sicily. Following the introduction in Louisiana, in 1904, of the Frasch method of producing sulfur, the United States became independent of outside sources (see Fig. 221) and soon had a surplus for exportation. This reduced the Sicilian miners to starvation wages. The United States now exports more than three times as much sulfur as Sicily produces and is capable of further expansion of its deposits, so the outlook for the Sicilian industry is bad.

The Sicilian Deposits.—The sulfur deposits of Sicily cover an area of 800 square kilometers. They vary greatly in richness. The sulfur occurs interstratified with limestone, gypsum, bituminous marls, clay, and sandstone. It occurs massive and crystalline. Celestite, barite, gypsum, and calcite occur with it. The ores range from 8 to 50 per cent sulfur, and those mined average from 20 to 25 per cent. The reserves are large.

Sicilian Mining Methods.—Although the Sicilian mining methods have been somewhat improved in recent years, they are still very crude. Most of the mining is done by hand; the ore is carried out in baskets. Much of the ore is still recovered by setting fire to a pile and allowing the heat of burning sulfur to melt the remainder. About 60 per cent of the sulfur is recovered by this method. More efficient methods of recovering it are being introduced.

The Deposits of Texas (and Louisiana).—The most important sulfur deposits in the United States and in the world are those in Texas. In 1928, Texas produced 99.88 per cent of the sulfur output of the United States. These deposits are all near the Gulf Coast (see Fig. 224, p. 547). There are four producing areas in this region: Freeport, Brazoria County; Matagorda, Matagorda County; Wharton, Wharton County; and Bena-vides, Duval County. The deposits occur in connection with the salt

¹ BASTIN, E. S., *The Problem of the Natural Reduction of Sulfates*, A.A.P.G. Bull., vol. X, pp. 1270–1299, 1926.

domes of the coastal region but are not found with all the domes. Most of the production at present comes from depths of 700 to 850 feet, but some deposits are known to extend 1,200 feet below the surface. The different deposits range from 200 to 1,500 acres in extent. The associated rocks are limestones, dolomite, gypsum, and salt. The sulfur-bearing beds are from 100 to 150 feet in thickness, and the percentage of sulfur in them ranges from 10 to 50. The element occurs as free sulfur.

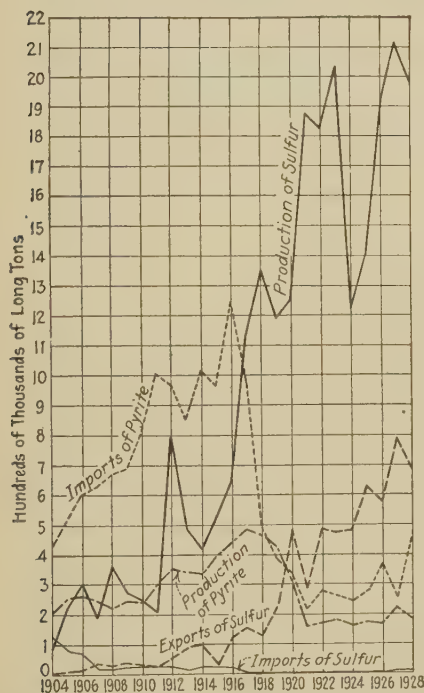


FIG. 221.—Curves showing the shift from a small sulfur production in the United States to a large production, and the influence upon a closely allied industry, the production of pyrite. (Data from U. S. Mineral Resources.)

Sulfur was discovered in 1865 in Calcasieu Parish, Louisiana, but because of the quicksands overlying it, all attempts at mining were failures until Frasch perfected his hot-water method in 1904. These deposits were extensively worked until they became exhausted in 1924. During their 20 years of existence, they produced 10,000,000 tons of pure sulfur.

The Hot-water Method of Extracting Sulfur.—The hot-water method of extracting sulfur is a simple one. It is illustrated and fully explained in Fig. 222. A large boiler capacity is needed for this process. When

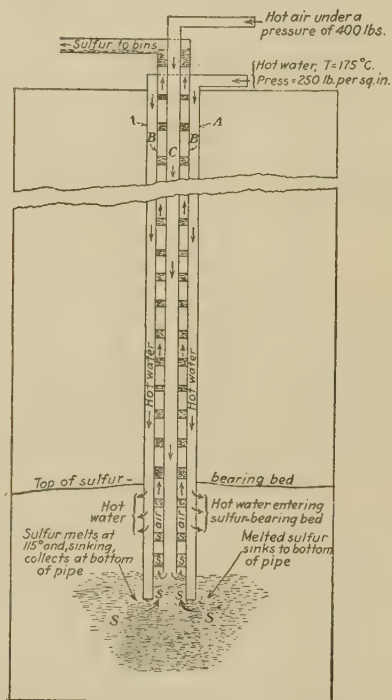


FIG. 222.—Ideal sketch of Frasch method of extracting sulfur by hot water and air. Pipe (A) is usually, 10 or 12 inches in diameter. The sulfur is carried upward by the air under pressure, a layer of sulfur alternating with a layer of air.

the melted sulfur (and some escaping water) reaches the surface, it flows by means of gravity to cooling bins. The wooden framework of the bins (which are about 150 by 250 by 65 feet and about 100,000 tons capacity) is then removed and the sulfur stands as a solid block. This is an ideal method of storage; in fact, some of the companies keep 1,000,000 tons or more of sulfur in reserve all the time. It has to be blasted down before shipping and is easily handled in loading. The sulfur obtained by this method is 99.5 per cent pure and is ready for direct use.

Minor Sulfur Deposits in the United States.—Small deposits of sulfur occur at Rabbit Hole mines, Humboldt County, and Cuprite, Esmeralda County, *Nevada*; Sulfurdale, Beaver County, *Utah*; Sulfur Bank, Lake County, *California*; and Cody, Park County, and Thermopolis, Hot Springs County, *Wyoming*.

USE OF SULFUR

The Importance of Sulfur in Industrialism.—Sulfur is a very essential product. So essential is it in manufacturing processes, that it has been said that a nation's consumption of sulfur is a measure of its industrial progress. This is well illustrated by the history of sulfur consumption in the United States. During the eighties of the last century, the United States used less than 100,000 tons of sulfur a year from all sources. In 1928, about 1,400,000 tons was used; the annual average for the 10-year period of 1917 to 1926 was 1,340,000 tons. These figures are an illuminating commentary on the recent rapid progress of industrialism in the United States. The United States now uses more sulfur than any other country and in 1928 produced 82 per cent of the world's supply.

The Chief Use of Sulfur.—The chief use (estimated to be over 50 per cent) of sulfur is *in making sulfuric acid*. There has been an interesting shift in the source materials for this purpose. The following table gives the sources of sulfur for the manufacture of sulfuric acid in the United States in 1914 and in 1926:

TABLE 104.—SOURCES OF SULFUR USED IN THE MANUFACTURE OF SULFURIC ACID IN THE UNITED STATES, 1914 AND 1926¹

Material	Percentage	
	1914	1926 ²
Pyrite (domestic and foreign).....	73.70	16.50
Smelters (copper and zinc).....	23.70	15.20
Native sulfur.....	2.60	68.30

¹ *Mineral Industry*, 1926, p. 638.

² Estimated by the author.

A total of 7,225,000 tons of sulfuric acid was used in the United States in 1928. The following table giving the estimates of the distribution of the uses of sulfuric acid for that year is of interest:

TABLE 105.—USES OF SULFURIC ACID IN THE UNITED STATES, 1928¹

Use	Amount used, tons
Fertilizer manufacture.....	2,300,000
Petroleum refining.....	1,350,000
Chemicals.....	745,000
Coal products.....	740,000
Iron and steel.....	695,000
Other metallurgical uses.....	600,000
Paints and pigments.....	210,000
Explosives.....	170,000
Textiles.....	130,000
Miscellaneous.....	285,000
Total.....	7,225,000

¹ U. S. *Mineral Resources*, 1928, Part 2, p. 61.

Use of Sulfur as Sulfite.—Approximately 25 per cent of the sulfur used in the United States is used as the sulfite SO_2 . By far the largest user of sulfite is the paper-pulp industry, which probably ranks as the second industry in the use of sulfur in the United States. About 250 pounds of sulfur is required to manufacture 1 ton of sulfite pulp. Over 175,000 tons of sulfur is used annually in this industry in the United States and Canada.

Uses of Raw Sulfur.—A large tonnage of sulfur is used for agricultural purposes, such as for fertilizers, insecticides, and fungicides for dipping. The rubber industry uses a large amount in making vulcanized rubber products. An acid-proof cement consisting of 40 per cent sulfur and 60 per cent sand is an important product; its tensile strength (400 pounds per square inch) is said to exceed that of Portland cement. As sulfur is a non-conductor of electricity and heat, it is used for both electrical and heat insulation.

PYRITE

Pyrite is a mineral of very widespread occurrence. Its name was given it by the Greeks from their word for fire. This was in reference to the fact that when struck it forms sparks, a property possessed by several other sulfides. Because in its color it resembles gold, it has long been called "fool's gold." This resemblance was the reason pyrite was the first mineral product shipped to England from the American colonies. The early settlers were all looking for gold; so, when some of Captain John Smith's party found a deposit of pyrite, a shipment was made as soon as possible.

Physical Properties and Composition of Pyrite.—Pyrite is a hard (it will scratch glass), pale, brass-yellow mineral. In form, it is crystalline

as well as massive. It is an iron sulfide, FeS_2 . It contains 53.4 per cent sulfur and 46.6 per cent iron. Rarely, it contains small amounts of copper or gold.

Mode of Occurrence of Pyrite.—Small crystals and concretions of pyrite are common in almost all types of rocks. Except for a few unusual bedded deposits, however, not many of these occurrences are workable. A small amount of pyrite is obtained in some districts as a by-product of coal mining. In the most important pyrite deposits, the mineral occurs as *veins*, *lenses* (Fig. 223), or *irregular masses* in igneous, metamorphic, and sedimentary rocks. Deposits containing millions of tons are known. Copper and, less commonly, gold occur with pyrite, and both are recovered if possible. Considerable marcasite usually occurs with pyrite in deposits that are near the surface.



FIG. 223.—Pyrite lenses (white areas) in schists at Sulfur Mines, Louisa County, Virginia. (After Watson, *Mineral Resources of Virginia, Va. Geol. Survey*, p. 194, 1907.)

Origin of Pyrite.—Little need be said about the origin of pyrite, for it may form from either cold or hot solutions and at the surface or deep within the earth. Whenever a soluble iron salt comes in contact with hydrogen sulfide, it is possible for pyrite to form. The large deposits, however, are directly connected with solutions that come from the interior of the earth. Some of these were formed deep within the earth's crust and have been exposed by subsequent erosion.

Distribution and Production of Pyrite in the United States.—There are many deposits of pyrite that cannot be worked; for, on account of the low value (\$2.50 to \$3.50 per ton), a deposit to be worth developing must be readily accessible for both mining and marketing. It is mined, however, in many parts of the United States (Fig. 224, p. 547).

Pyrite Deposits in Eastern United States.—Many deposits of pyrite occur throughout the eastern part of the United States, especially in the eastern Appalachian area, and all have contributed somewhat to the pyrite production.

Virginia has always been the largest pyrite-producing state in the east. The mines are located near Mineral and Sulfur mines, Louisa County; at Dumfries, Prince William County; and at Garrisonville, Stafford County. The pyrite occurs as lenses (see Fig. 223) in quartz-mica schists. These lenses parallel the structure of the rocks and are

of various lengths up to several hundred feet and of widths up to 60 or 80 feet. They have been mined downward to considerable depths. The pyrite is believed by Watson to have replaced limestone, after which the whole was metamorphosed.

Other pyrite deposits of the eastern crystalline belt are smaller than those in Virginia. The pyrite occurs as lenses in schists and gneisses. These deposits are located near Canton, St. Lawrence County, *New York*; Davin, Franklin County, *Massachusetts*; Acworth, Clay County, *Alabama*; and Villa Rica, Carroll County, *Georgia*.

Pyrite Deposits of Western United States.—The largest deposit of pyrite worked in the United States is that near Keswick, Shasta County, *California*. This contains as high as 3 per cent copper and \$2 per ton gold. The deposits are tabular replacement masses of pyrite and minor amounts of chalcopyrite. They occur in sheared and brecciated zones of an igneous rock (alaskite porphyry). Some of the mineral masses are 1,200 by 300 by 300 feet and weigh millions of tons. Most of the pyrite is treated to recover the copper, but some is sold directly for making sulfuric acid.

A small production of pyrite is made as a by-product from coal mining in *Indiana*, *Ohio*, and *Illinois*. Many small deposits are known throughout the *Rocky Mountain region*.

Foreign Pyrite Deposits.—Important deposits of pyrite are worked in *Spain*, *Italy*, *Norway*, *Germany*, *Canada*, *Sweden*, *Japan*, and *France*.

Pyrite Deposits of Spain.—The pyrite deposits of Spain greatly exceed all the other foreign deposits in size and productivity. They occur in the southwestern part of the country and extend across into Portugal. The pyrite belt in the provinces of Huelva and Seville is 80 miles long and 25 miles wide. The most famous mines are those on the coast near Rio Tinto, 30 miles from the city of Huelva.

The pyrite occurs as lenses in slates and porphyries. Magmatic waters are believed to have formed it by replacing some of the slate and porphyry along sheared and broken zones. The lenses are of great size. No less than 50 are known which are from 1,200 to 6,500 feet long and from 500 to 1,800 feet thick. The deposits are worked mainly as open cuts. Estimates of the reserves range from 300,000,000 to 1,000,000,000 tons, and the estimated life of the mines at the present rate of production is 100 years. The ore runs from 48 to 51 per cent sulfur. Spain exported 393,840 tons of pyrite to the United States in 1928.

Use of Pyrite.—The chief use of pyrite is in making sulfuric acid. About 640,000 long tons was used for this purpose in the United States in 1928.

Fluctuations in the Use of Pyrite for Making Sulfuric Acid.—The changes in the respective amounts of native sulfur and pyrite used for

making sulfuric acid in the United States are worth noting briefly. In the early eighties of the last century, 85 per cent of the sulfuric acid made in this country was made from sulfur (obtained mainly as an import from Sicily). This percentage decreased slowly as pyrite was substituted; in 1895, 75 per cent of the acid was still being made from sulfur. At about this time, however, owing to the undue raising of the price of Sicilian sulfur to \$18 to \$19 per ton, pyrite was rapidly substituted in acid plants. By 1900, very little sulfur was used for acid making. Pyrite continued to be the chief source of sulfur for making acid until 1916, when war demands caused the acid industry to substitute sulfur as a source material on account of the consequent shortening of the process of acid making. The domestic production of sulfur was adequate for this purpose, and the use of pyrite practically stopped. In 1921, less than 400,000 tons of pyrite was used. In 1928, however, the sulfur producers in the United States fixed the price of sulfur at \$19 per ton, and the acid makers are again turning to the use of pyrite. An increase of 83 per cent in our imports of pyrite in 1928 indicated this change. This is the largest amount of pyrite we have imported since 1919.

Selected Readings on Sulfur and Pyrite

- CLARKE, F. W.: *Data of Geochemistry*, U. S. Geol. Survey *Bull.* 770, pp. 586-588 (sulfur); pp. 336-339 (pyrite).
- LEITH, C. K.: "Economic Aspects of Geology," pp. 107-111, Henry Holt & Company, 1921.
- LADOO, R. B.: "Non-metallic Minerals," pp. 465-471, 600-615, McGraw-Hill Book Company, Inc., New York, 1925.
- LINDGREN, WALDEMAR: "Mineral Deposits," pp. 421-428 and numerous references to pyrite, McGraw-Hill Book Company, Inc., New York, 1928.
- Mineral Industry, Ann. Repts.*, McGraw-Hill Book Company, Inc., New York.
- U. S. Mineral Resources*, and the earlier reports of the U. S. Geological Survey.
- WATSON, T. L.: "Mineral Resources of Virginia," Va. Geol. Survey, p. 190, 1907.
- Excellent bibliographies are found in most of the above references.

SALT

Salt is the only mineral which man requires regularly as a food. Animals, especially herbivores, will travel long distances to reach a salt spring or salt "lick." It is estimated that each person requires an average of 12 pounds of salt annually as a food. In those countries where salt is scarce, very high values are placed upon it, and it is regarded as a rare delicacy. In the desert regions of Africa, caravans pass through the country peddling it. In parts of Africa, a man (considered as a laborer) is worth just about his weight in salt.

Although much salt is obtained in Europe by evaporation of sea water, large quantities of it are mined. A single mine, near Cracow, Poland, has been producing it for over 600 years. During that time, 30 or 40

miles of tunnels have been excavated. This mine is only one of many important salt mines in Europe, as other countries are similarly supplied with large deposits.

The first utilization of the salt deposits in the United States, according to the earliest record we have, was made about 1670, when the mineral was secured by evaporation of water from springs in New York.

Composition of Salt.—The mineralogical name of salt is “halite.” In composition, it is sodium chloride, NaCl. It is seldom pure, however, but contains small amounts of calcium, magnesium, and potassium sulfate and chloride. Calcium and magnesium compounds are more common than those of potassium. The following analyses illustrate the composition of salt:

TABLE 106.—ANALYSES OF ROCK SALT FROM NEW YORK, MICHIGAN, KANSAS, AND LOUISIANA¹

Radicals	Percentages of material soluble in water			
	1	2	3	4
K.....	0.2	Trace	Trace	Trace
Na.....	36.00	38.80	38.30	39.10
Ca.....	1.96	Trace	0.80	Trace
Mg.....	0.50	0.30	Trace	0.10
Cl.....	59.94	59.80	60.00	59.90
SO ₄	1.13	1.00	0.80	0.90

1. Sample from Retsof Mining Company, Retsof, New York. Taken from middle of salt bed, 1911. J. A. Cullin, analyst.

2. Samples from Detroit Salt Company, Detroit, Michigan. Taken from roof to floor of working face, 1911. R. F. Gardiner, analyst.

3. Samples from Bevis Rock Salt Company, Lyons, Kansas. Taken from top to bottom of 16-foot bed, 1911. R. F. Gardiner, analyst.

4. Sample from Avery Rock Salt Company, Avery Island, Louisiana. Taken from working face, 1911. R. F. Gardiner.

¹ PHALEN, W. C., Salt Resources of the United States, U. S. Geol. Survey *Bull.* 669, p. 216.

The presence of calcium and magnesium compounds in salt makes the salt subject to deliquescence.

Physical Properties of Salt.—Salt has a hardness of 2.5. It crystallizes in the cubic system and has a perfect cubic cleavage. Perfect crystals are rare, however, occurring only in open cavities or on the surface. Rock salt is massive: its grains range from minute crystals to those 10 or 12 inches across. These large crystals are usually perfectly clear, and many of them enclose cavities which contain water and a gas (probably air). This water was included in the salt crystals during their process of growth. Salt crystals grow with little hopper-shaped

cavities on their sides; and, if these do not fill out so rapidly as the outer edges, cavities result in which the water is sealed.

For the most part, rock salt is gray, yellow, pink, or red, but some is blue (supposed to be due to metallic sodium particles), brown, or black. Salt is readily soluble in water, which is the property that controls many of its uses.

Geologic Age of Salt Deposits in the United States.—Salt is found in the United States in rocks of various ages, from the Silurian to the present (see Table 107). Its distribution within the rocks of a given period is always local. The most widespread deposits are those of the Permian formation.

The salt beds of Permian age extend southwest from northern Kansas across Oklahoma and Texas into New Mexico, a distance of about 650 miles. The width of the belt is from 50 to 150 miles. The area of the deposits is about 100,000 square miles, and the beds have an average thickness of 200 feet. If these assumptions are correct, over 30,000,000,000,000 tons of salt is available in the region.

Although the salt domes are in Tertiary beds, the mineral is believed by some to have originated in the Cretaceous formations; but Permian or Triassic beds are a far more likely source of this salt.

The following table shows the geologic and geographic distribution of the salt deposits in the United States:

TABLE 107.—GEOLOGIC AND GEOGRAPHIC DISTRIBUTION OF THE SALT DEPOSITS OF THE UNITED STATES¹

Age	Region
Recent.....	Great Salt Lake and numerous lakes in New Mexico, Texas, Nevada, Oklahoma, Utah, and California
Tertiary.....	Louisiana and Texas (salt domes), Nevada (Virgin River), Idaho, and Wyoming
Jurassic.....	Utah
Permian.....	Kansas, Oklahoma, northwestern and western Texas, and eastern New Mexico (possible source of salt in salt domes in Louisiana and Texas)
Pennsylvanian.....	Southern Ohio and West Virginia
Mississippian.....	Michigan, Virginia, and Pennsylvania
Silurian.....	New York, Michigan, and northern Ohio

¹ Modified from table by Phalen in U. S. Geol. Survey *Bull.* 669, p. 193.

Distribution of Salt Deposits in the United States.—The distribution of the salt-producing localities in the United States is shown in Fig. 224. Salt could be produced elsewhere but the present producing localities more than meet the demand. Over 68 per cent of the salt used comes from natural and artificial brines, the remainder from rock salt deposits. Rock salt is mined in New York, Kansas (Fig. 225), Louisiana, Utah, and California.

MODE OF OCCURRENCE OF SALT

Salt occurs as *rock salt in beds* interstratified with shales, sandstones, and limestones; as *surface deposits* in the beds of dried-up lakes, marshes, and playas; and in *natural brines*.

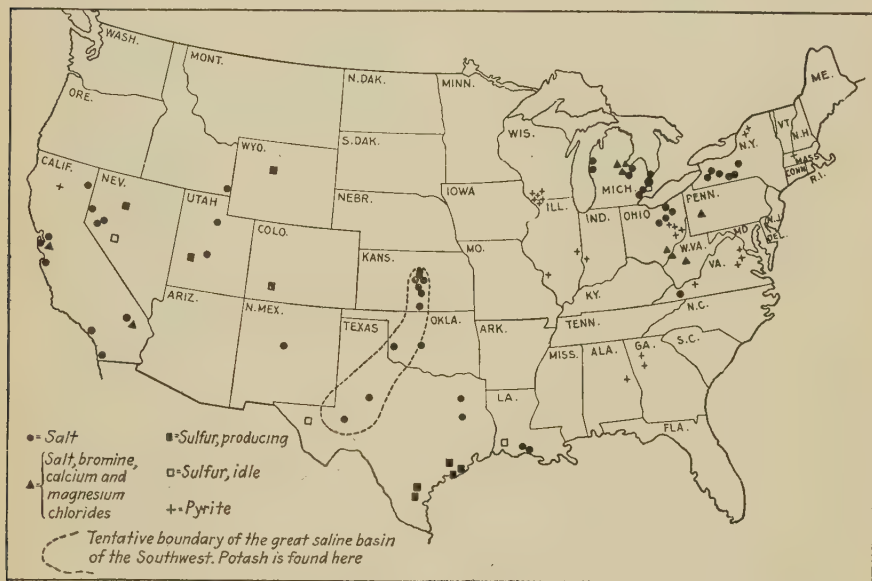


FIG. 224.—Map showing the location of the salt, bromine, calcium and magnesium chloride, and sulfur and pyrite areas of the United States. (Data from U. S. Geol. Survey; Bur. Mines; and other sources.)

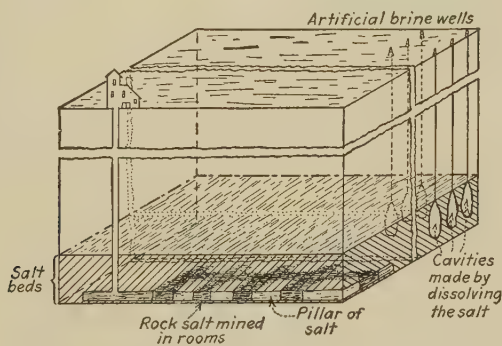


FIG. 225.—Stereogram illustrating the two methods of producing salt used by the American Salt Corporation at Lyons, Rice County, Kansas. Rock salt is mined by the room and pillar method, and artificial brines are made by pumping water down to the salt member and dissolving the salt. (Based on figure furnished by the American Salt Corporation.)

Rock Salt. *Thickness of Beds.*—Rock-salt beds range from a few inches in thickness to nearly 400 feet. In the salt domes, thicknesses of 4,000 feet occur; the domes, however, are not beds but columns of salt.

A thickness of 318 feet of salt is reported in a well at Tully, New York. One hundred feet of pure salt is exposed along the Virgin River in Clark County, Nevada (Fig. 226), and this does not represent the full thickness, as the base of the bed is not exposed.

A shaft at Little River, Rice County, Kansas, reached the first bed of salt at 558 feet and passed out of the last one at 845 feet. In 287 feet of salt-bearing beds, there were 18 beds of salt ranging in thickness from 2 to 31 feet and totaling 191 feet. As many as 32 salt-bearing layers have been noted in some Kansas wells.

The Permian basin in eastern New Mexico and western Texas has remarkable salt beds. A given section may contain dozens, many of great thickness. Several beds having thicknesses of 300 to 400 feet are known. A core-drill hole, 20 miles east of Carlsbad, New Mexico, revealed nearly 1,300 feet

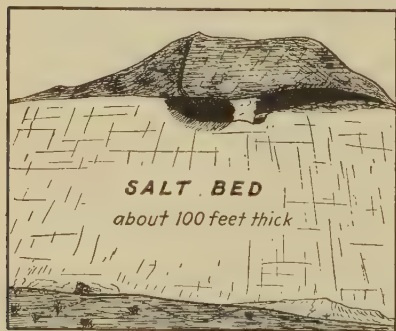


FIG. 226.—Sketch of a bed of salt forming a cliff in an arroyo near Virgin River bottom, 5 miles south of St. Thomas, Nevada. Black areas at top of bed represent solution cavities in the salt. (Modified from Darton, U. S. Geol. Survey Bull. 669, pl. XIII, p. 146.)

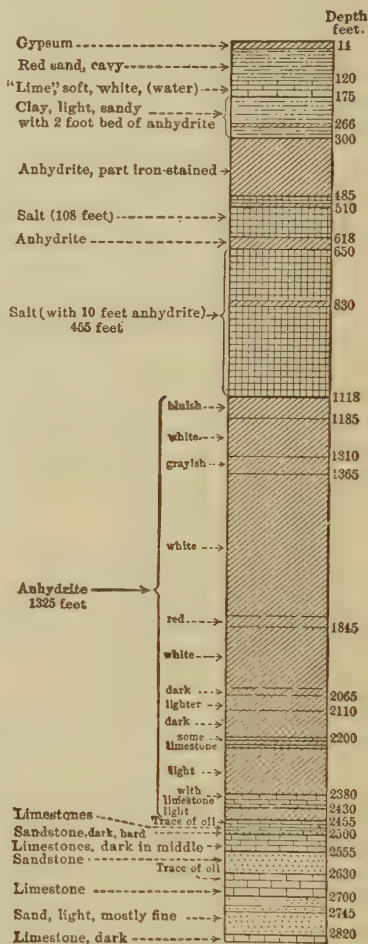


FIG. 227.—Log of a well 2 miles east of Carlsbad, New Mexico, showing salt, anhydrite, and gypsum. (Darton, U. S. Geol. Survey Bull. 697, Fig. 29, p. 176.)

of salt with interbedded deposits of potash minerals. A log of a well (near Carlsbad) showing salt, gypsum, and anhydrite is given in Fig. 227.

Associated Rocks.—Rock-salt beds are usually associated with shales, sandstones, gypsum, and anhydrite. Anhydrite is generally more closely

associated with the salt than gypsum, but both may be entirely absent. Anhydrite is very abundant in the salt deposits of the Permian basin and in the salt and potash deposits at Stassfurt, Germany. In the latter deposits, the layers of salt are separated by $\frac{1}{4}$ inch of anhydrite, which, it is believed, was deposited in winter, the salt being deposited in summer. On this assumption, 9,900 years were required to deposit the lower salt bed at Stassfurt.

More rarely, limestone and dolomite occur interbedded with the other rocks of a salt series, and both are then probably of chemical origin (*i.e.*, the result of direct chemical precipitation on the sea floor).

The Salt domes.—The salt domes of the Gulf Coast (and other parts of the world) represent an unusual mode of occurrence of salt. They consist of vertical columns of rock salt, surrounded by the Tertiary (and Mesozoic) sediments through which they penetrate. The name "dome" was applied to them because of the arched character of the beds over the salt columns and as the salt itself is not domed. Some of the columns, as those in the Five Islands in Louisiana, reach nearly to the surface; others are at depths of 1,000, 2,000, or 4,000 feet. Gypsum and limestone or dolomite usually rest upon the salt, with shales and sandstones above them.



FIG. 228.—Contorted salt in salt dome in Myles salt mine, Weeks Island, Louisiana. This shows how the salt has flowed during its movement upward. (After Veatch, *U. S. Geol. Survey Bull.* 669, pl. 11, p. 114.)

The rocks surrounding the columns are shales and sandstones of Tertiary age. They are folded upward adjacent to the salt and are slickensided at the contact. The salt is intensely contorted and folded (see Fig. 228).

The actual area of the salt columns is small, as they range from only a few hundred to 1,500 feet or more in diameter, but their depths are remarkable. The drill penetrated 2,740 feet of salt at Belle Isle, Louisiana, and 3,879 feet in a salt column at Sperenberg, Germany. The greatest thickness, 5,140 feet, is reported from a well at Humble, Texas.

Surficial Deposits of Salt.—Salt occurs in lake basins, in the sands and clays of salt marshes, and on the surfaces of playas. In the sands and clays, it is in layers; is interbedded with other saline materials; or is mixed with the sand and clay. Crusts of salt form on playas or salt plains during the dry season and are a local source of the mineral. This type of deposit is unimportant economically.

Natural Brines.—There are three common types of natural brines: brines occurring in sandstones (and other porous rocks); the brines of lakes; and the sea water.

Brines Occurring in Rocks.—Brines occur in sandstones of many ages, but those of most value in the United States are found in the Mississippian and Pennsylvanian formations. The brines of the Marshall sandstone in Michigan (Fig. 229) and of the Big Salt sand in Ohio are of Mississippian age; those at Pottsville in West Virginia are Pennsylvanian. The brines of these localities contain bromine and calcium chloride in addition to salt. Brines are common throughout the United States and are found in a great many oil fields.

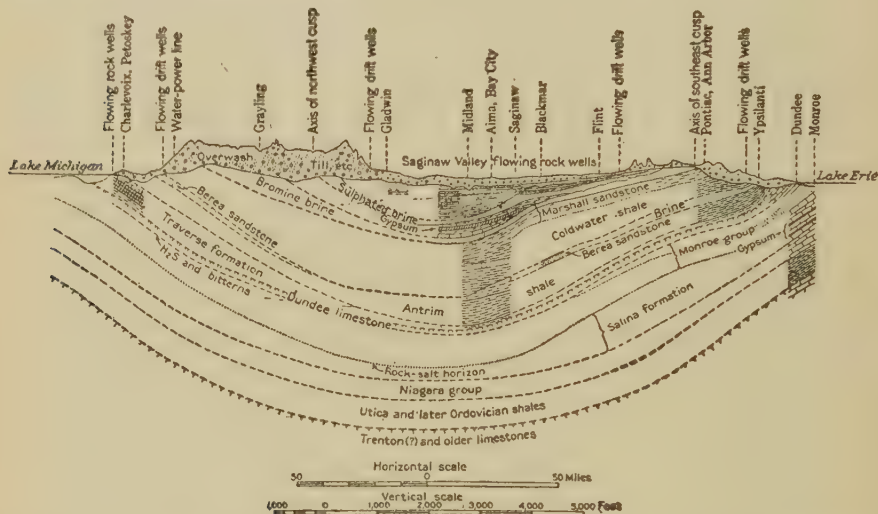


FIG. 229.—Geological structure of the Michigan Basin, showing the salt and brine horizons. (Phalen, *U. S. Geol. Survey Bull.* 669, p. 45.)

The composition of some brines is shown in the following table:

TABLE 108.—COMPOSITION OF BRINES¹

Radicals	Percentages of materials soluble in water		
	1	2	3
K.....	0.00	0.27	0.12
Na.....	21.99	30.84	38.88
Ca.....	11.54	5.10	0.31
Mg.....	2.71	1.76	0.00
Cl.....	62.35	61.71	59.81
SO ₄	0.38	0.00	0.88
Br.....	0.69	0.32	0.00
Fe.....	0.25	0.00	0.00
NH ₄	0.09	0.00	0.00
Totals.....	100.00	100.00	100.00

¹ Data from *U. S. Geol. Survey Bull.* 669.

TABLE 108.—COMPOSITION OF BRINES (*Continued*)

1. Natural brine. Sample from Dow Chemical Company, Midland, Michigan. Composite of 12 wells, 1911. R. F. Gardiner, analyst.
2. Natural brine. Sample from Mason Coal and Chemical Company, Hartford, West Virginia. R. K. Bailey, analyst.
3. Artificial brine. Sample from Colonial Salt Company, Kenmore (near Akron), Ohio. R. F. Gardiner, analyst.

Brines of Lakes.—Brines occur in enclosed lakes having no outlet. Great Salt Lake and numerous other lakes in the Great Basin; the Dead Sea; and Salton Sea are examples of such lakes.

Sea Water.—The sea water has long been an important source of salt and will continue to be in spite of the numerous other sources.

ORIGIN OF SALT DEPOSITS

The origin of salt deposits is apparently very simple, yet some elements of the problem are rather complex.

Origin of Rock Salt.—As salt occurs interstratified with other sediments, it is a sedimentary rock, but its origin is chemical.

Source of the Salt.—The original source of the sodium chloride of our salt deposits is the ocean (unless some of our saline formations are epicontinental in origin). The following table shows the composition of the sea water by radicals and by the probable salts present:

TABLE 109.—COMPOSITION OF AVERAGE SEA WATER¹

Radicals	Percentage	Probable compounds	Percentage
Cl.....	55.292	Sodium chloride, NaCl	77.758
Br.....	0.188	Magnesium chloride, MgCl ₂	10.878
SO ₄	0.792	Magnesium sulfate, MgSO ₄	4.737
CO ₃	0.207	Calcium sulfate, CaSO ₄	3.600
Na.....	30.593	Potassium sulfate, K ₂ SO ₄	2.465
K.....	1.106	Magnesium bromide, MgBr ₂	0.217
Ca.....	1.197	Calcium carbonate, CaCO ₃	0.345
Mg.....	3.725		
Totals.....	100.000	.....	100.000

¹ Data from U. S. Geol. Survey *Bull.* 669, pp. 217–219.

The amount of salt in the ocean is great. The total amount of saline matter is estimated at 4,800,000 cubic miles. Salt, NaCl, comprises 77.76 per cent of this, or 4,392,480 cubic miles. This volume of salt would make a layer slightly over a mile in thickness over the entire United States, Alaska, the Philippines, and Hawaii. If it were all piled on Texas, the layer would be 16.7 miles thick.

Order of Crystallization of Sea Salts.—When sea water is evaporated, the various substances in it crystallize out as the solution becomes

saturated with them. Since their solubilities are different, they are deposited in succession. This order is: (1) calcium carbonate; (2) calcium sulfate; (3) sodium chloride; and (4) magnesium and potassium compounds. The fact that the ocean contains very little calcium carbonate (although nearly twice as much is added to it annually as any other salt) is largely due to its removal from solution by the organisms in the sea. Gypsum and salt occur together in many geologic horizons, but of the two, the former is the more apt to occur alone; and it is more common as a rock than salt, though the latter is the more abundant constituent of sea water. The reason for this lies in the greater insolubility of calcium sulfate in the sea water; therefore, in an evaporating body of water the gypsum comes down first. If a fresh influx of sea water occurs, or (due to some diastrophic event) the basin where deposition is going on is drained, no salt would be deposited, and gypsum would occur alone. If, however, further concentration by evaporation occurs after the crystallization of the gypsum, the salt will be deposited. The very soluble magnesium and potassium salts remain in solution to the very last, forming the final solution known as the "bittern." This ideal sequence is influenced by numerous factors. The solubility of any substance is influenced by the presence of other substances, by the temperature, and by the concentration of the solution. It is remarkable that this sequence has occurred (at least up to the bittern stage) so many times during geologic history and that pure deposits of each compound have been made.

Origin of Thick Beds of Sea Salts.—Some salt deposits (aside from those of the salt-dome type) are of such exceptional thickness that their origin requires special consideration and explanation. Thousands of feet of sea water must be evaporated to form a deposit of salt several hundred feet thick, and there is no evidence that such deep waters ever existed where salt deposits are found; in fact, the evidence is exactly opposed to such a possibility. Many investigators have sought to explain these great thicknesses of salt.

Ochsenius, in 1877, suggested that a body of sea water might be shut off from the sea by a bar across which influxes of sea water occurred from time to time. The water in the basin would evaporate; and, if the influxes of sea water occurred at sufficiently long intervals, evaporation would bring about the deposition of gypsum (or anhydrite) and salt. (Anhydrite rather than gypsum is deposited from a strongly saline solution, as such a solution would dehydrate any gypsum deposited.) If conditions were right, the series of events postulated by Ochsenius would have been repeated many times, as was apparently the case during the formation of the salt deposits at Stassfurt, Germany. The final drying up, without draining, of such a bay or body of water would bring about the deposition of the potassium and magnesium salts. Such

deposition occurred in the deposits at Stassfurt, and recent explorations in western Texas and in New Mexico have shown that, to some degree at least, it occurred in the great Permian basin of that area.

Grabau made the alternative (to the theory of Ochsenius) suggestion that the salt in the Silurian formation was derived from connate waters in the underlying Niagara beds, the waters' having been carried through erosional processes into a basin where they were concentrated and their salt deposited in Silurian strata. Branson (see discussion under Gypsum) has suggested that preliminary concentration of the solutions occurred in one or more basins, from which the solution overflowed into the final basin where precipitation occurred.

Origin of Very Pure Deposits of Salt.—The bar theory of Ochsenius merely explains the thick deposits of the alternating saline minerals, not thick deposits of pure salt; though the theory could be modified to explain the pure deposits. Branson's theory best accounts for very pure beds of salt, as the overflow solution from one lake to the other would be largely of the same composition.

A point of considerable importance affecting any of the above theories has to do with the time in the sequence of deposition of the various salts. The statement is made by some authors¹ that gypsum separates from sea water after 37 per cent of the water is evaporated, and salt when 93 per cent has evaporated. Others² state that 80 per cent of the water must be evaporated before gypsum is deposited, which is the figure given by Usiglio, who published the results of his studies of the evaporation of sea water in 1849.

The difference between these figures for the concentration of the solution that would deposit gypsum would have an important bearing upon the origin of pure deposits of both gypsum and salt and in determining the conditions of their association. If gypsum is deposited when 37 per cent of the water is evaporated, a long interval will ensue before salt is laid down, easily permitting independent deposition of each mineral and thus pure deposits of each. If 80 per cent of the water must be evaporated before gypsum is deposited, only a very narrow margin of time will be available between the periods of deposition, and a nice balance of chemical and physical factors will be necessary to make possible pure deposits of each. The greater concentration of the solution, furthermore, would favor the universal formation of anhydrite rather

¹ RIES, H., "Economic Geology," p. 246, 1925.

LEITH, C. K., "Economic Aspects of Geology," p. 295, 1921.

HAWORTH, E., Gypsum Deposits of the United States, U. S. Geol. Survey Bull. 697, p. 120, 1920.

² STONE, R. W., Gypsum Deposits of the United States, U. S. Geol. Survey Bull. 697, p. 22, 1920.

CLARKE, F. W., Data of Geochemistry, U. S. Geol. Survey Bull. 491, p. 207.

LINDGREN, WALDEMAR, "Mineral Deposits," p. 331, 1928.

than gypsum, whereas the widespread occurrence of pure gypsum beds unassociated with salt would indicate that deposition took place at a lower concentration. Gypsum, anhydrite, and salt occurring together favor, but do not *require*, the higher concentration. Indeed, gypsum occurring with anhydrite and salt is also commonly accompanied by sandstone, clay, limestone, and dolomite; so the presence of gypsum probably means a freshening of the water, as it would be hard to account otherwise for these interbedded deposits.

Origin of Salt Domes.—The origin of the salt domes or columns has already been discussed under Petroleum (p. 414). The columnar character of the salt mass, the upturned beds, the slickensiding, and the contorted character of salt layers within the columns are taken to mean that the salt has come to its present position by moving upward from some unknown source, which is believed to be Permian beds. This upward movement was probably due to the weight of the overlying sediments causing the salt to move upward along fault planes or broken zones that had penetrated to the salt horizon. As before stated, the fundamental factor making this movement possible is the highly perfect cleavage of salt along three planes at right angles to each other. These planes permit the salt to glide or flow under pressure, and it moves upward in the direction of the least pressure.

Origin of Surficial Deposits.—The deposits of salt in lake basins, marshes, and playas are the result of the final evaporation of a saline water. The deposits contain all the other materials that were originally in solution.

Origin of Brines. *Origin of Brines Occurring in Rocks.*—The brines found in rocks are believed to be buried sea waters, the evidence being especially strong where bromine and other salts now found in the sea are contents of the brines. Buried sea waters are connate waters.

Some brines may have acquired their salt content by leaching salt out of the associated rocks.

Origin of Brines of Lakes and Seas.—The origin of the salt in the brines of lakes and the sea is, of course, the long-continued accumulation in the bodies of water of the salt brought into them in minute quantities by the streams.

USES AND PRODUCTION OF SALT

Uses of Salt.—The largest use of salt is in manufacturing numerous sodium salts, such as sodium carbonate, caustic soda, and soda ash. It is also an important source of chlorine and hydrochloric acid. Large amounts of salt are used in seasoning and preserving foods. Other uses are in refrigeration, in making glazes and enamels on pottery and granite-ware and salt glazes on sewer tile, as a food for cattle, in the dyeing

industry, in soap manufacture, and as a scale remover in steel rolling mills.

Production of Salt in the United States.—Unlike most other mineral products, the amount of salt mined does not fluctuate with industrial conditions but shows a slow, steady growth with the increase in population; a situation to be expected when a product is used so extensively for food or in the preparation and preservation of foods.

Brines are used directly in most of the chemical manufacturing plants; 3,426,870 tons were so used in the United States in 1928. This was 42 per cent of the total salt production that year. The production of salt in the United States from 1880 to 1928 is shown in Fig. 230.

Selected Readings on Salt

GRABAU, A. W.: "Principles of Salt Deposition," McGraw-Hill Book Company, Inc., New York, 1920.

LADOO, R. B.: "Non-Metallic Minerals," pp. 479-498, McGraw-Hill Book Company, Inc., New York, 1925.

LEITH, C. K.: "Economic Aspects of Geology," pp. 294-298, Henry Holt & Company, New York, 1921.

LINDGREN, WALDEMAR: "Mineral Deposits," pp. 328-353, McGraw-Hill Book Company, Inc., New York, 1928.

PHALEN, W. C.: Salt Resources of the United States, U. S. Geol. Survey Bull. 669, 1919.

RIES, H.: "Economic Geology," pp. 210-228, John Wiley & Sons, Inc., New York, 1925.

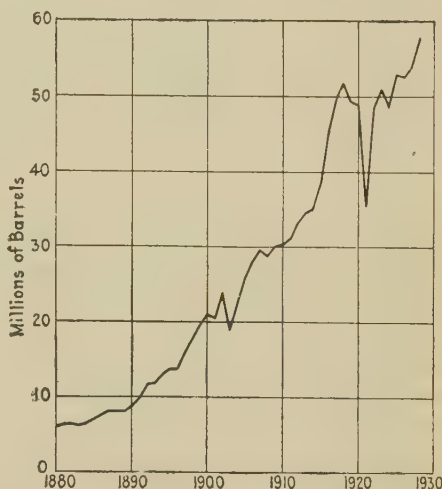


FIG. 230.—Curve showing the production of salt (in barrels of 280 pounds each) in the United States from 1880 to 1928. (Data from U. S. Mineral Resources and Mineral Industry.)

FERTILIZERS

A fertilizer is any substance that will improve the physical or chemical condition of the soil. The use of fertilizers is no modern innovation. Man recognized the need of replenishing certain substances in the soil hundreds of years before he knew what the substances were.

Phosphates, potash, nitrates, sulfur, and lime are essential plant foods. Such substances as *gypsum, limestone, and marl* are of value in correcting the physical condition of the soil; for example, in making a clay soil more granular and porous. These substances are normally present in soils and are slowly renewed as they are lost at the surface. The annual decay of the vegetation on the surface returns to the soil those substances used by

the plants, minus small amounts lost through leaching by ground waters. During farming operations, the removal of crops causes losses of these substances that are greater than can be renewed each year. Leith¹ states that "a ton of wheat takes out of the soil on an average 47 pounds of nitrogen, 18 pounds of phosphoric acid, 12 pounds of potash." Such losses, unless made up, inevitably cause a decrease in the fertility of a soil. As yet, the need of fertilizers for the soil in the United States is not so great as in the older tilled areas of Europe and Asia, but it is essential.

The United States has an abundant supply of phosphate rock but very limited quantities of nitrates and potash.

PHOSPHATE ROCK

Phosphate rock is a sedimentary rock containing calcium phosphate. The phosphate exists as an amorphous mass, usually as the colloidal minerals collophanite, $9\text{CaO} \cdot 3\text{P}_2\text{O}_5 \cdot \text{CaO} \cdot \text{CO}_2 \cdot \text{H}_2\text{O} - n\text{H}_2\text{O}$, and fluor-collophanite. In some phosphates, the amount of fluorine closely approaches the ratio necessary for apatite, which is a crystalline form of calcium phosphate occurring in igneous and metamorphic rocks. Apatite rarely occurs in sufficiently large quantities to be mined.

Composition of the Economic Product.—The commercial phosphate must contain from 75 to 80 per cent tricalcium phosphate, $\text{Ca}_3\text{P}_2\text{O}_8$. It is not desirable to have more than 3 per cent iron and aluminum, because they form insoluble phosphates during the manufacture of the acid phosphate. Sand and carbonates are also undesirable constituents. The material mined at present is generally run through a log washer for cleaning.

Mode of Occurrence of Phosphate Rock.—The phosphate rock occurs as *beds* associated with limestone, marl, sandstone, and shale; as *pebbles* and *boulders* in streams crossing beds of phosphate rock; and as *residual deposits* over calcareous beds.

Bedded Deposits.—The bedded phosphate deposits are the most extensive and have the largest reserve tonnage, though they contribute only a small part of the annual production. They range widely in composition: from 1 to 80 per cent lime phosphate. The phosphate rock varies widely in color and texture. Some beds are oolitic, others have an abundance of fossils, and others are massive. The beds are usually 1 or 2 feet thick, but a few are 6 or 7 feet.

Pebble and Boulder Deposits.—The pebble and boulder phosphate deposits are the result of the concentration of the more insoluble phosphatic rock along the streams crossing phosphate beds. These deposits were formerly an important source of phosphate.

Residual Deposits.—The residual phosphate deposits have resulted from the leaching of the limestone and marls in phosphatic beds, the

¹ LEITH, C. K., "Economic Aspects of Geology," p. 99.

insoluble lime phosphate concentrating at the surface as the more soluble materials were removed. Such deposits are found overlying phosphatic beds or at their outcrop.

Origin of Phosphate Rock.—Organisms are probably the source of the phosphoric acid in phosphate rock, as all animals, especially land animals, obtain more or less phosphorus from their food. This phosphorus becomes part of the bones or shells of the organism or is thrown off as excrement. Wherever animal life is abundant and the remains can accumulate, phosphate deposits may form. The phosphate deposits of South Carolina are directly associated with the bones of animals.

The extensive and rich phosphate beds found in Utah, Wyoming, Idaho, and Montana are regarded by Mansfield and others as being direct chemical deposits. The sea water in which the rock was laid down had become enriched in phosphorus, probably through the decay of organic materials on the sea floor. This phosphate reacted with calcium carbonate to form calcium phosphates. The calcium phosphate was deposited as the amorphous phosphate, as oolites, and as replacements of calcareous shells.

Some phosphate deposits (as those in Florida) are believed to have been formed through the leaching of guano. The phosphoric acid was carried down and reacted with limestone. Later, this limestone was exposed and the phosphate was further concentrated by leaching and redeposition. Some of the phosphate rock in Florida may have been deposited as phosphatic sands and nodules on the sea floor, as is suggested by the presence of phosphatic materials in some of the present waters about Florida. The immediate source of the phosphate in the phosphatic sands and nodules of these waters is unknown.

A phosphate deposit may originally be of low grade; but, through the removal of the associated limestone, the relatively insoluble phosphates may be left behind as a residual deposit. Also, under favorable conditions, phosphates may be carried downward by ground waters into limestones, where the tricalcium phosphate may be formed by reactions with the calcium carbonate of the limestone. The phosphate deposits of Tennessee, Kentucky, and Arkansas are examples of residual deposits.

Phosphate Deposits in the United States.—The phosphate areas of the United States are found in the southeastern part of the country and in the Rocky Mountain region (see Fig. 231). Florida, Tennessee, South Carolina, Kentucky, and Arkansas all contain deposits, but only the first two states are important producers; in fact, they produced, in 1928, 98.8 per cent of the phosphates mined in the United States. Although undeveloped as yet, there are enormous deposits of a high-grade phosphate rock in Idaho, Utah, Wyoming, and Montana.

Phosphate Deposits of Florida.—The phosphate deposits of Florida occur in a narrow belt about 100 miles long. This belt is located 6 to

20 miles inland from the Gulf Coast. The deposits are of Tertiary age. There are three classes of phosphate: *hard rock pebble*, *land pebble*, and *river pebble*.

The *land pebble phosphate* is produced in the largest quantities. It consists of erosional pebbles of phosphate rock from the Alum Bluff phosphatic marl (Oligocene). The pebbles are mixed with sand, gravel, and clay. The main bed is from 8 to 20 feet thick, averaging 10 to 12 feet. The average phosphate content is from 65 to 75 per cent. The most important producing region of this phosphate is a circular area about 30 miles across lying just east of Tampa.

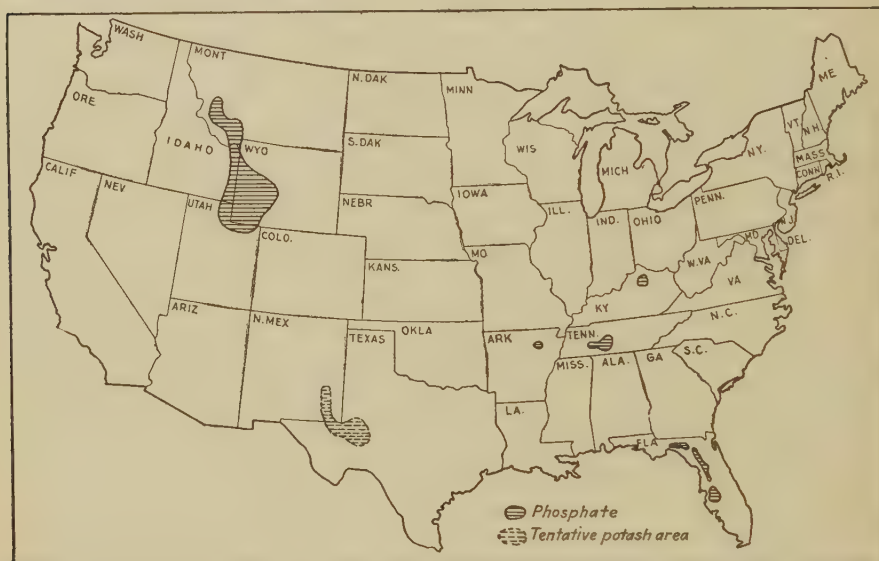


FIG. 231.—Map of United States showing the location of the important phosphate areas (boundaries approximate) and the area where potash minerals are being found in the Permian formations in Texas and New Mexico.

The *hard rock pebble phosphate* occurs as rock boulders embedded in fine clay, sand, and soft phosphate. This is the highest-grade deposit (maximum 80 per cent phosphate), but the total quantity of phosphate produced from it is small (3.2 per cent of the Florida production in 1928).

Tennessee Phosphate Deposits.—The phosphate in Tennessee occurs in the west-central and extreme northeastern parts of the state. Although three varieties occur, only one, the brown rock, is extensively mined. It occurs as residual material concentrated through the weathering of a phosphate-rich limestone of Ordovician age. The rock is found principally in Maury, Giles, Hickman, Sumner, and Lewis counties. A little blue phosphate (Devonian) is mined, also.

Other Eastern Phosphate Deposits.—The *Kentucky* phosphate deposits are in the vicinity of Lexington. Only a small production is made.

The Arkansas deposits are low-grade phosphate but are of large extent. The South Carolina deposits are in a belt near the coast.

The Western Phosphate Deposits.—Idaho, Utah, Wyoming, and Montana probably contain the greatest deposit of phosphate rock in



FIG. 232.—Map showing extent of western phosphate fields of the United States. (After Condit, Finch, and Pardee, U. S. Geol. Survey Bull. 795, pl. 10, p. 166.)

the world (see Fig. 232). The rock is believed to be a true sedimentary rock. It is interbedded with limestone and shale. One bed, 3 to 6 feet thick, is widely distributed throughout this field. This bed averages a 65-per cent content of tricalcium phosphate.

The phosphate rock is oolitic, gray to brown or black in color, and usually emits a fetid odor when struck with a hammer. The oolites range up to $\frac{3}{16}$ inch in diameter and are embedded in a dense, fine-grained matrix. The beds are from a few inches to several feet in thickness. They occur in the Carboniferous formation (probably Pennsylvanian and Permian).

In Utah, the deposits occur in the Wasatch and Uinta Mountains. The area extends across southeastern Idaho (where the richest deposits occur) and southwestern Wyoming (where exposures are found in the Owl Creek, Wind River, and Gros Ventre ranges). Deposits occur also in west-central Montana. Very little phosphate has been mined in these states because of the long distances from a market, but the deposits constitute an enormous reserve for the future, probably billions of tons. Idaho, alone, has about 5,000,000,000 tons of phosphate that runs from 65 to 84 per cent tricalcium phosphate. Much of these deposits is on government land and, thus, will be fully protected against excessive exploitation. At the present rate of phosphate consumption, the United States could supply the entire world with phosphates for hundreds of years to come.

Uses of Phosphate.—Phosphate rock finds its largest use in fertilizers. It may be used raw (the finely ground rock being spread directly on the land), but the greater part of it is converted into a readily soluble form by treating it with sulfuric acid. One pound of phosphate rock requires slightly more than one pound of sulfuric acid in this treatment. These soluble forms are known as “acid phosphates” or “superphosphates.” The former term is a more correct name, for superphosphate would seem to imply a *greater* content of P_2O_5 . The maximum amount of P_2O_5 in the soluble product, however, is 18 per cent, and the original rock contains about 60 per cent. A high-grade, soluble phosphate (45 to 50 per cent P_2O_5) is made by the Anaconda Company of Butte, Montana, from Idaho phosphate. Over 1,897,000 tons of sulfuric acid was used in making acid-phosphate in the United States in 1927.

Other uses of phosphate are for making phosphorus and phosphate chemicals. Blast furnaces use considerable amounts of phosphate rock in making ferrophosphorus. Small quantities are employed in manufacturing refractory brick and in prepared stock foods, such as a chicken grit.

Selected Readings on Phosphates

- LADOO, R. B.: “Non-Metallic Minerals,” pp. 419–436, McGraw-Hill Book Company, Inc., New York, 1925. Contains a good bibliography.
- LINDGREN, WALDEMAR: “Mineral Deposits,” pp. 316–327, McGraw-Hill Book Company, Inc., New York, 1928.
- MANSFIELD, G. R.: Geography, Geology, and Mineral Resources of Part of South-eastern Idaho, U. S. Geol. Survey *Paper* 152, 1927.

- MATSON, G. C.: The Phosphate Deposits of Florida, U. S. Geol. Survey *Bull.* 604, 1915. Excellent account.
- MERRILL, G. P.: "The Non-Metallic Minerals," p. 270, John Wiley & Sons, Inc., New York, 1910.
- RIES, H.: "Economic Geology," pp. 260-283, John Wiley & Sons, Inc., New York, 1925. Contains an excellent bibliography.
- STONE, R. W.: Spurr's "Political and Commercial Geology," pp. 402-410, McGraw-Hill Book Company, Inc., New York, 1920.
- VAN HORN, F. R.: The Phosphate Deposits of the United States, U. S. Geol. Survey *Bull.* 394, pp. 157-171, 1909.
- U. S. Mineral Resources and Mineral Industry* also contain material of much interest as well as good lists of references.

POTASH

So essential is potash as a plant food that about 90 per cent of all potash salts produced in the world goes into fertilizers. Cotton, potatoes, tobacco, and citrus fruits are some of the plants which must have potash.

Mode of Occurrence of the Potash Salts.—Potassium occurs in a number of silicates, especially in orthoclase and microcline, two common feldspars. During weathering, the potassium of the silicates is liberated as potash and is absorbed by the hydrous aluminous minerals and by the colloidal silica formed during the weathering. A part of the potash is removed in solution, finding its way into the streams where some of it is taken up by the muds and deposited with them on the sea floor. The remainder of it accumulates in the sea water. In the original igneous rock, the amounts of potassium and sodium are nearly equal; in the streams, the ratio is 1 part potassium to 4 parts sodium; and in the ocean, it is 1 part potassium to 30 parts sodium. There can be little doubt but that the first plants utilized the ever present potash in the soil in their cell processes, and all plants since then have continued to do so—an interesting case of adaptation.

Source of the Potash Used in the United States.—There are no deposits of potash worked in the United States. All the potash produced here comes from treating brines and kelp and as by-products from numerous manufacturing processes (from dust of cement plants, for example). In 1928, 104,000 short tons of potash was produced in these ways in the United States. This was 9.6 per cent of what was required.

For years, the greater part of the potash we use has come from the deposits at Stassfurt, Germany, which are the largest deposits known. Not only the United States but also all countries have been dependent upon Germany for potash, and Germany has controlled the output and prices. New deposits discovered in 1904 in Alsace have made France an important potash producer, and she now shares with Germany the control of the market.

Potash Production during the World War.—During the World War, the normal supply of potash from Germany was cut off; and, as the price

of it rose, domestic production in the United States increased until it reached a maximum in 1919. This amount, however, totaled only about one-sixth of our imports of potash in 1913. The potash produced during this time was derived from many sources most of which have proved to be temporary. The most important of these were the alkali lakes of western Nebraska; brines from Searles Lake, California; kelp; distillery wastes, especially those from molasses used in making industrial alcohol; and alunite, a potash mineral.

The German Potash Deposits.—The German potash deposits represent the final deposition of sodium, potassium, and magnesium salts in an inland sea in which these substances had been concentrating for a long time. As a result of this long period of concentration, there is an enormous deposit containing over 30 different minerals (mostly chlorides and sulfates), that were deposited when the basin dried up. The deposits are estimated to contain 20,000,000,000 metric tons of potash salts—enough to supply the world, at the present rate of use, for 2,000 years.

Potash Deposits of France and Spain.—The Alsace potash deposits also have a large reserve and could supply the world for 300 years. Important potash deposits were discovered in Spain in 1913 but have been only moderately developed, and little is known of their total reserves.

Potash Deposits of the United States.—The lack of adequate potash deposits led the U. S. Geological Survey to investigate the areas where the geology was favorable to their possible occurrence. As a result of this survey, evidence of such deposits was found in western and southwestern Texas and eastern New Mexico. Further careful investigations have revealed a thick series of Permian beds containing salt; gypsum; anhydrite; important quantities of polyhalite, $K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$; and small amounts of other potash minerals, such as carnallite, $KCl \cdot MgCl_2 \cdot 6H_2O$, sylvite, KCl , and kainite, $MgSO_4 \cdot KCl \cdot 3H_2O$. The potash minerals are in beds as thick as 8 feet, and they occur from 350 to 1,500 feet below the surface (the German mines are from 1,000 to 2,500 feet deep). The potential area of these potash deposits has recently been greatly extended by the discovery of potash-bearing beds in the numerous oil wells drilled in southwestern Texas and eastern New Mexico. Figure 224 (p. 547) shows the location of these potash deposits in the United States.

A little alunite, $K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$, is mined at Maryvale, Utah. The deposit is a vein of solid alunite, 3,500 feet long, and averaging 10 feet in width.

The greensands of numerous localities are possible sources of potash. Glauconite is the potash-bearing mineral in these sands, but the total amount of potash in any greensand is low, averaging about 6.6 per cent.

Uses of Potash.—Aside from the use of potash in fertilizers (which is 95 per cent of all its uses in the United States), it is employed in making soaps (of highest grades), drugs, glass, matches, and explosives, and in tanning, dyeing, photography, and metallurgy. There are 40 or more potash salts in common use.

Selected Readings on Potash

Information on potash is widely scattered. Much material can be found in the references listed under Phosphates.

CLARKE, F. W.: Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, pp. 222-229.

Origin of the deposits of Stassfurt, Germany.

GALE, H. S.: Potash Deposits in Spain, U. S. Geol. Survey *Bull.* 715-A, pp. 1-16, 1920.

—: Potash Deposits in Alsace, *idem.*, pp. 17-55.

HOOTS, H. W.: Geology of a Part of Western Texas and Southeastern New Mexico; with Special Reference to Salt and Potash. U. S. Geol. Survey *Bull.* 680, pp. 33-126.

MANSFIELD, G. R.: Potash in the Greensands of New Jersey, U. S. Geol. Survey *Bull.* 727, 1922.

NITROGEN COMPOUNDS

As nitrogen is an essential plant food, it must be added to soils that are depleted of it.

Occurrence of Nitrogen in Nature.—The atmosphere is the ultimate source of all nitrogen, from which it is utilized in various ways (see Fig. 233). Free nitrogen forms 79 per cent of the atmosphere, but in this state plants are not able to make use of it for food. They must have it in the form of nitrates or other soluble nitrogen compounds, such as ammonium sulfate. Nitrogen, however, does not readily unite with other elements. A natural way in which it may be changed into nitrates is through the action of certain bacteria (known as "nitrifying bacteria") which live in the roots of legumes.

Processes of Nitrogen Fixation.—Where a sufficient amount of cheap power is available, nitrogen fixation (*i.e.*, the conversion of free nitrogen into a form which can be used as plant food) has been accomplished on a commercial scale. Sweden and Norway, having an abundance of water power, have accomplished much in this direction.

The *Haber process*, largely used in Germany, produces ammonia, NH_3 , by subjecting nitrogen and hydrogen to heat and pressure in the presence of a catalyzer. *Sodium cyanide*, NaCN , is made in limited amounts by passing nitrogen through a red-hot mixture of soda ash, Na_2CO_3 ; coke; and iron. *Calcium cyanamide*, CaCN_2 , which is probably the most important product of nitrogen fixation, is made by allowing hot ($1,000^\circ\text{C}.$) calcium carbide to absorb nitrogen. The plant at Muscle Shoals, Alabama, was designed to produce this product. It is doubtful whether this project will ever become a commercial success, however, as politics have become mixed up with it. *Ammonium sulfate* is produced as

a by-product of the manufacture of coke in the retort oven and is extensively used for agricultural purposes. The value of the ammonium sulfate from this source in the United States in 1927 was nearly \$25,000,000. Little has been done to develop a commercial method of fixing nitrogen by using nitrifying bacteria, although this would appear to offer the greatest opportunity of any of the processes.

Other Sources of Nitrogen.—Other sources of nitrogen are from sewage, garbage, manures, and refuse from packing houses. All these materials are utilized to some extent as fertilizers or in making fertilizers.

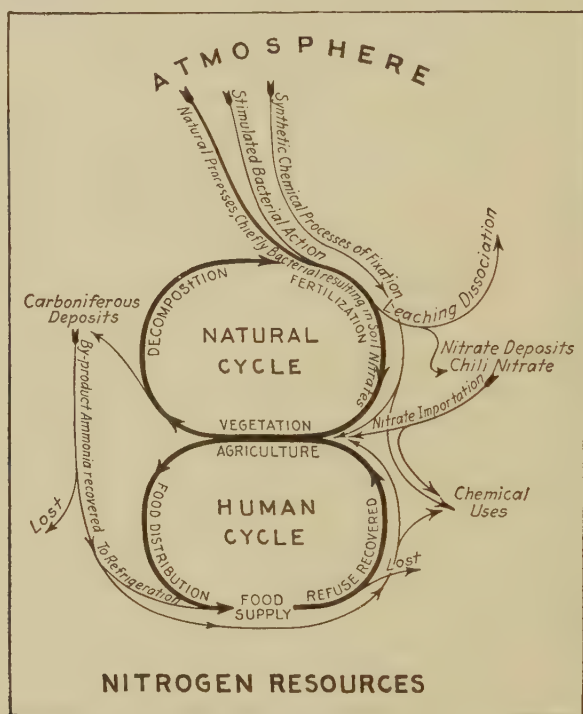


FIG. 233.—Nitrogen sources and their cycles of utilization. (After Gilbert, Spurr's "Political and Commercial Geology," p. 427, 1920.)

Nitrate Deposits.—The United States does not contain a single important deposit of nitrate. There are numerous insignificant deposits, such as guano deposits in caves, but these do not supply more than a fraction of 1 per cent of what is needed.

The Chilean Nitrate Deposits.—The chief deposits of natural nitrate in the world are in Chile. They are in the desert of Atacama in the northern part of the country, in a basin lying between the coast range and the Andes. The nitrate rock, known as "caliche," is as much as 6 feet in thickness and lies just below the surface. The nitrate occurs as sodium

nitrate (called "Chile niter"). It contains a little potassium nitrate (saltpeter). The crude nitrate has a variable composition, as may be seen from the following table:

TABLE 110.—RANGE OF COMPOSITION OF THE CHILEAN CRUDE NITRATE¹

Compounds	Percentage composition
NaNO ₃	22.0 to 62.0
KNO ₃	0.0 to 17.0
NaCl.....	3.0 to 42.0
CaCl ₂	0.0 to 5.0
MgCl ₂	0.0 to 1.0
Na ₂ SO ₄	0.0 to 6.0
MgSO ₄	0.0 to 10.0
CaSO ₄	1.0 to 5.0
Na ₂ B ₄ O ₇	0.2 to 0.6
NaI.....	0.0 to 0.5
NaIO ₃	0.01 to 1.0
H ₂ O.....	0.05 to 6.5
Na ₂ CrO ₄	Traces

The world's supply of iodine is largely obtained as a by-product from these deposits, although the amount present, as shown above, is always small.

¹ Data from PENROSE, *Jour. Geol.*, vol. XVIII, p. 14, 1910.

The origin of these nitrate deposits is still an open problem. Fixation of nitrogen by lightning, leaching of guano deposits, leaching of nitrates produced by nitrifying bacteria, a volcanic origin, and other suggestions have been made. A volcanic source seems best to fit the conditions.

The Production of the World's Supply of Nitrogen.—The importance of the Chilean nitrate deposits in the world's production of nitrogen has greatly decreased in recent years due to the artificial production of nitrogen compounds. The following table shows this decrease:

TABLE 111.—DECLINE IN CHILEAN NITRATE PRODUCTION

Year	Percentage of world's production made by Chile
1894	73
1913	53
1925	26

It is thus readily seen how rapidly the various methods of nitrogen fixation have been gaining ground.

Selected Readings on Nitrogen Compounds

- CLARKE, F. W.: Nitrates, Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, pp. 254–259, 1924. This is a discussion of the origin of nitrate deposits.
- GILBERT, C. G.: Spurr's "Political and Commercial Geology," pp. 421–446, McGraw-Hill Book Company, Inc., New York, 1920. This contains a very fine analysis of the entire nitrogen situation—one of the best available.
- LADOO, R. B.: "Non-Metallic Minerals," pp. 403–416, McGraw-Hill Book Company, Inc., New York, 1925. An excellent account of the Chilean nitrate deposits.

MISCELLANEOUS MATERIALS

Sulfur.—Recent studies in soil fertility have shown that sulfur is fully as important as phosphates as food for certain crops. Ordinary cereals use two-thirds as much sulfur as phosphorus; grasses use about the same amount of each; and cabbage and turnips use two or three times as much sulfur as phosphorus. Fortunately, this sulfur is furnished by the acid phosphate, which contains some sulfur acquired during its manufacture from sulfates. The use of gypsum as land plaster is also beneficial for furnishing sulfur.

Lime.—Plants require some calcium, but the amount is not large. Most vegetables, some fruits, alfalfa, clover, barley, wheat, oats, and timothy are benefited by lime. The plants injured by it are radish, flax, blackberry, black raspberry, and cranberry.

The lime (quicklime or hydrated) is of value for converting humic acids into more insoluble forms; consequently, they are retained in the soil. Lime aids in preventing injurious bacteria from growing in the soil and stimulates the growth of nitrifying bacteria. A very important use is to neutralize an acid condition of the soil, and another is to render clayey, sticky soils more porous and granular.

Limestone may be utilized for these purposes, but it reacts less rapidly than lime.

Glaucanite.—Greensands contain varying amounts of glauconite, a hydrous silicate of iron and potash. The potash in the glauconite is of value as a plant food, but it is less readily accessible than the other forms of potash fertilizers which are applied to the soil. Certain formations in New Jersey contain considerable amounts of glauconite averaging about 6 per cent potash. Several Mesozoic formations along the Gulf Coast contain glauconite, which is not of commercial importance, however.

NATURAL SODIUM COMPOUNDS

Immense quantities of sodium salts are used today, most of which are artificial. The majority are made from sodium chloride, but some are obtained as by-products in the manufacture of other products.

Some of the natural sodium compounds marketed are *borax*, $\text{Na}_2\text{O} \cdot 2\text{B}_2\text{O}_3 \cdot 10\text{H}_2\text{O}$; *kernite*, $\text{Na}_2\text{O} \cdot 2\text{B}_2\text{O}_3 \cdot 4\text{H}_2\text{O}$; *colemanite*, $2\text{CaO} \cdot 3\text{B}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$; *ulexite*, $2\text{CaO} \cdot \text{Na}_2\text{O} \cdot 5\text{B}_2\text{O}_3 \cdot 16\text{H}_2\text{O}$; *sodium carbonate*, Na_2CO_3 ; *sodium bicarbonate*, NaHCO_3 ; *trona*, $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$; *mirabilite*, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$; and *thenardite*, Na_2SO_4 .

The production of these sodium salts in the United States amounted in 1928 to 206,380 tons, valued at \$5,272,228.

Sodium Borate Compounds. *Borax*.—Borax has been important in the chemical industry for years. Formerly, it was chiefly obtained from Italy, where it occurs in gases escaping from volcanoes. It was later discovered in the brines of several lakes in *California*, *Nevada*, and *Oregon* and was secured from them by evaporation. It is also found in this region in the deposits of dried-up lakes. "Twenty-mule-team borax" is a trade name which illustrates the difficulties of getting the product to market in the early days. About half the 1928 production of borax in the United States was obtained as a by-product during the recovery of the potash and soda ash from the brines of Searles Lake, San Bernardino County, *California*.

Ulexite.—The chief mineral found in the deposits of the dried-up lakes, however, is ulexite. Until 1882, these lakes and marshes were the principal source of borax in the United States.

Colemanite.—About 1882, large deposits of colemanite (and some ulexite) were discovered in Death Valley, Inyo County, *California*. Other discoveries of colemanite followed rapidly, and until 1926 this mineral was by far the most important source of our borax.

The colemanite in the Death Valley deposits occurs as irregular masses replacing a limestone which is interbedded with shales. Basalt is associated with the deposits and is regarded as the source of the boric acid that replaced the limestone. The deposit south of Lang, Los Angeles County, is about 85 feet thick and dips about 75°. Colemanite must be converted into borax.

Kernite.—In 1926, the discovery of a new sodium borate, kernite (named from Kern County, *California*, where it was discovered), was announced. One deposit of it is near Amargo, Kern County, and another near Kramer. The mineral occurs in crystals some of which are several feet long. It is found throughout 80 feet of clays and sands, at a depth of 400 feet. The remarkable thing about this mineral is that it dissolves readily in water and then upon evaporation to a saturated solution crystallizes out as normal borax.

The simplicity and cheapness of producing borax from kernite has been the cause of the closing of most of the colemanite mines. Only a small production was made from them in 1928, and that was from a Nevada deposit.

Uses of Borates.—Most borates are converted into borax or boric acid. In the case of colemanite and ulexite, the process of conversion into borax is expensive; in the case of kernite, it is very cheap.

In Enamels.—The dominant use of borax is in the manufacture of enamels for enameled ware (so-called "granite ware"). Bathtubs, kitchen sinks, cooking utensils, and numerous articles are made from this ware. Borax fuses readily and acts as a flux for the other materials in the enamels.

Households Uses.—Borax and boric acid are sold by all druggists for many domestic requirements. The former is a convenient water softener for the kitchen and laundry. Borax soaps are good in very hard water. Some starches and cosmetics (as borated talcum powder) contain borax. It is good for keeping out cockroaches and ants. Boric acid has an antiseptic value and is used in eye lotions and various dressings for wounds.

Miscellaneous Uses.—Considerable borax is converted into various chemicals which have a wide use. It is employed in making borosilicate glass for dishes ("pyrex" type); laboratory glassware, such as beakers and flasks; incandescent lamps; and lamp chimneys. It gives to glass a low coefficient of expansion, which makes the glass but slightly susceptible to changes in temperature. Its use also gives to the glass added refractiveness. When other acid oxides are added to the borax mixture, the resulting glass is likewise very resistant to chemical action. Borax is used in making pottery glazes, in making surfaced or glazed papers, and in making a preparation (1 part borax and 5 parts shellac) for stiffening hats.

Borax has a wide use in assaying, in smelting precious metals, and in brass melting. A very extensive use is in welding and brazing. The borax has the property of easily dissolving the metallic oxides on the surface of the metal to be brazed or welded, leaving it clean for the process. Borax is used in determinative mineralogy, as it dissolves the oxides of certain metals which impart to the borax characteristic colors. Borate of chromium is Guignet green, a beautiful color.

Tanning requires considerable borax, which enters into several steps of the process, even to the final dyeing. Borax is used for dyeing textiles (excellent as a mordant), for fireproofing certain cloths, and for degumming silk.

During 1926, a new use was found for borax that may call for considerable amounts. This was as a preservative.

Lemons dipped in a 5-per cent solution of borax at 115°F. for 5 min. keep in excellent condition for periods longer than a month in an ordinary shed, whereas the untreated fruit shows the development of molds to the extent of from 8 to 15 lemons per case after 5 days storage.¹

The sodium borate minerals produced in the United States in 1928 amounted to 131,000 tons, valued at \$3,999,773. This was 75 per cent of the total value of all the natural sodium compounds produced.

Sodium Carbonates.—The three common forms of sodium carbonate are Na_2CO_3 (soda ash), NaHCO_3 (sodium bicarbonate, baking soda), and $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$ (trona). All three minerals are found in the

¹ MANNING, P. D. V., *Mineral Industry*, 1926, p. 90.

deposits of dried-up (or nearly dried-up) lakes in the western states. These compounds are even more common than salt in some of the lakes, which, as a result, are often called "soda lakes." Sodium sulfate may also be found in the same lake or deposit.

In 1928, the production of the sodium carbonates in the United States was wholly in *California* and came mainly from Owens Lake, Inyo County. A small production was made from Searles Lake, San Bernardino County. Other localities have furnished some sodium carbonate. These are Soda Lakes, Ragtown, *Nevada*; Long Valley (southeast of Mono Lake), Vernon, and Dorris, *California*; Grant County, *Washington*; Green River and Laramie (southwest of), *Wyoming*; and Antioch, *Nebraska*.

The method of securing sodium carbonate at Owens Lake, *California*, is to evaporate the brine until trona is deposited. This is then calcined, a process which converts it into soda ash. If the bicarbonate is desired, the brine is treated with carbonic acid gas just before trona begins to crystallize, and the bicarbonate is then formed.

Soda ash is one of the cheapest of alkaline compounds and finds a ready market for many industrial processes. In 1928, the production of it in the United States amounted to 79,930 tons, valued at \$1,578,256 (\$19.64 per ton, or about 1 cent per pound).

Sodium Sulfate.—Sodium sulfate occurs in deposits similar to those of the sodium carbonates but in less abundance. In addition to its occurrence in brines, it is found as mirabilite, which is identical with the artificial Glauber's salt, and as the anhydrous salt thenardite, which is identical with the artificial product salt cake.

The chief localities where sodium sulfate occurs in brines are Soda Lake (southwest of McKittrick), San Luis Obispo County, and Searles Lake, San Bernardino County, *California*; Downy Lakes and Union Pacific Lakes, Albany County (southwest of Laramie), several lakes in Sweetwater Valley and Gill Lakes, Natrona County (northeast of Casper), *Wyoming*; and Great Salt Lake, *Utah*.

Deposits of thenardite occur in Donna Ana County, *New Mexico*; at Clarkdale (near Camp Verde), Yavapai County, *Arizona*; and at Wabuska (near Yerington), Lyon County, *Nevada*.

The total production of sodium sulfates in the United States in 1928 amounted to 6,580 tons (valued at \$42,485), which was a decrease of more than 66 per cent from the 1926 production.

Selected Readings on Sodium Compounds

- CLARKE, F. W.: Data of Geochemistry, U. S. Geol. Survey *Bull.* 770, pp. 234-254, 1924.
- GALE, H. S.: Salines in the Owens, Searles, and Panamint Basins, *California*, U. S. Geol. Survey *Bull.* 580, pp. 251-323.

- LADOO, R. B.: "Non-Metallic Minerals," pp. 558-577, McGraw-Hill Book Company, Inc., New York, 1925. Good. Contains bibliography.
- RIES, H.: "Economic Geology," pp. 231-238, John Wiley & Sons, Inc., New York, 1925.
- WELLS, R. C.: Sodium and Sodium Compounds, *U. S. Mineral Resources*, 1918, Part 2, pp. 159-198.
Mineral Industry contains considerable information.

FLUORITE AND CRYOLITE

FLUORITE

Deposits of fluorite (not so satisfactorily called "fluorspar") have been known in the United States for nearly 100 years, but the mining and marketing of the mineral did not begin until in the early seventies of the last century. Apparently, it began at about the same time in both Illinois and Kentucky, but the difficulty of getting the Kentucky product to the Ohio River for shipment soon caused the mines there to be closed. They were opened again for a couple of years in the eighties, and active production began in 1896. The total production in the United States during this period was small, as the chief uses of fluorite were for making hydrofluoric acid and in the manufacture of opalescent glass, and only small amounts were needed for these purposes. In 1899, the amount used was doubled, due to the discovery by metallurgists that fluorite was superior to limestone as a flux in the basic open-hearth process of making steel. From the date of this discovery, the production increased rapidly.

Composition of Fluorite.—Fluorite is calcium fluoride, CaF_2 , and, if pure, contains 48.9 per cent fluorine and 51.1 per cent calcium. Chlorine is present in small quantities in the fluorite of some deposits, and other impurities which may occur are SiO_2 , CaCO_3 , Fe_2O_3 , Al_2O_3 , and S. In the use of fluorite, the composition must be known. The following table illustrates the variation in the composition of fluorite for different requirements:

TABLE 112.—COMPOSITIONS OF FLUORITE NECESSARY FOR CERTAIN OF ITS USES¹

Use	CaF_2	SiO_2	CaCO_3	Fe_2O_3	Al_2O_3	S
By steel plants.....	87.50	4.00	7.20	0.60	0.55	0.120
In glass and enamel.....	97.40	1.55	0.54	0.14	0.26	0.027
In hydrofluoric acid.....	99.07	0.24	0.38	0.	292	0.018
By iron foundries.....	87.00	4.50	7.50	0.00	0.00	0.000

¹ Data from U. S. Bur. Mines, 1926.

Physical Properties of Fluorite.—Fluorite is always crystalline. It crystallizes in the isometric system, and the most common form is the cube, which may be modified on the corners by the octahedron. The

cubes may attain the unusual size of 12 inches. Most fluorite consists of cleavable, crystalline masses or aggregates of cubes. Less commonly, fluorite is granular or compact.

Fluorite may be green, purple, pink, blue, yellow, brown, white, gray, or colorless. Its hardness is 4, and its specific gravity is 3.01 to 3.25. Fluorite has a very good cleavage, which is octahedral.

Mode of Occurrence of Fluorite.—Fluorite occurs in veins in sedimentary (usually limestone) and igneous rocks. It is also common as a gangue mineral in many mineral deposits, for it is able to exist under a wide range of physical conditions.

Origin of Fluorite.—In all its occurrences, fluorite shows direct evidence of having been formed from solutions that originated in igneous rocks. Its common occurrence in deposits of many kinds of minerals the origin of which was undoubtedly igneous also indicates for fluorite an igneous origin.

Some investigators have contended that the Kentucky-Illinois fluorite was not derived from igneous rocks. There seems to be little doubt, however, but that it was, although the peridotite dikes of the area may not have been the source but rather a deeper-lying igneous rock. Bain has suggested that the solutions from this rock were fluosilicates of zinc, lead, and barium, but the singular absence of quartz in the rocks of the district does not support this view.

Some men have regarded limestone as essential to the formation of fluorite (as the source of the calcium), but the fluorite occurrences in igneous rocks show that it is not essential.

Distribution of Fluorite in the United States.—Fluorite is found in small quantities as a gangue mineral in many parts of the United States, but workable deposits of the mineral are restricted to a few areas (Fig. 234). The production in 1928 was from Kentucky, Illinois, Colorado, New Mexico, and Nevada, but deposits also occur in some other states.

Kentucky-Illinois Fluorite Deposits.—The fluorite deposits of Kentucky and Illinois are essentially one, and the mode of occurrence of the fluorite in the two places is similar. This district is one of the largest and most productive fluorite areas in the world. The Illinois mines are in Hardin and Pope counties; the Kentucky mines, in Crittenden, Livingston, and Caldwell counties. There is another district in north-central Kentucky in Woodford and Mercer counties, but the production there is small. Illinois and Kentucky have long led in the production of fluorite in the United States. They were responsible for 96.4 per cent of the total production in 1928.

The country rocks of the ores throughout the district are limestones, sandstones, and shales. Dikes of mica peridotite occur but not in immediate association with the fluorite veins. The sedimentary rocks

are nearly horizontal but are very much faulted. The veins of fluorite occur in the fault fissures, filling them, cementing a breccia along them, or replacing the wall rock (Fig. 235). The veins may attain a width of

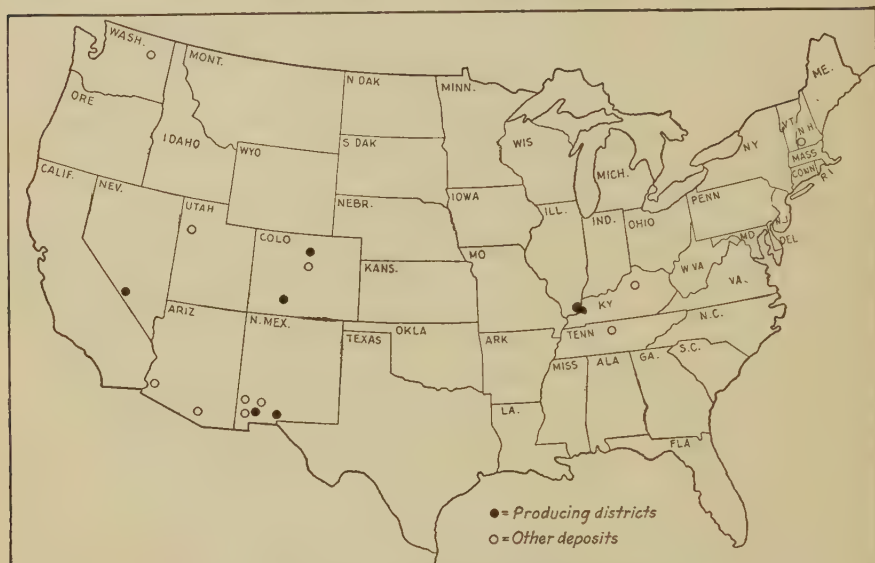


FIG. 234.—Fluorite deposits of the United States.

45 feet, largely as a result of replacement. Associated with the fluorite are calcite, sphalerite, galena, and barite. The best fluorite is found near the footwall of the vein; solid masses 10 feet across are not

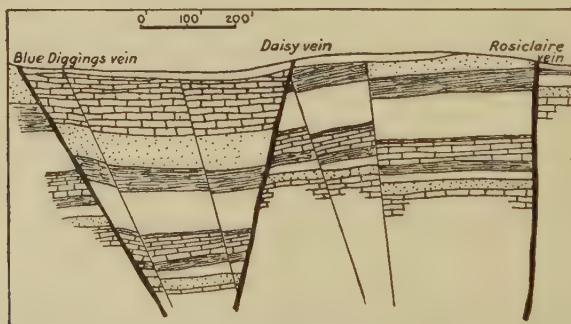


FIG. 235.—Geologic section through the Blue Diggings, Daisy, and Rosiclair fluorite veins at Rosiclair, Ill. Black areas represent fluorite veins. (After Spurr, *Eng. and Min. Jour.*, vol. CXXII, Nov. 6, 1926.)

uncommon. The upper parts of the veins show considerable weathering, the fluorite having broken down into a granular aggregate. Due to the insolubility of the fluorite, it has been more or less concentrated in this weathered zone.

Several grades of fluorite are mined, the best of which attains a very high degree of purity. Crushing and washing are used to separate the fluorite from the gangue minerals. As a result, gravel fluorite (sizes of less than 1 inch) is the chief product (86.5 per cent of the total in 1928). In Kentucky, 1,941 tons of ore are treated to secure 1 ton of fluorite, and in Illinois, 1,675 tons.

Colorado Fluorite Deposits.—There are numerous small deposits of fluorite in Colorado, but only three are productive. One deposit is at Wagon Wheel Gap, Mineral County; another is near Jamestown, Boulder County; and the third is near Cowdrey, Jackson County. The first two localities are the important producers.

In the Boulder County deposits, the fluorite occurs as veins cutting granites and gneisses. Numerous other minerals are associated with it. The deposit at Wagon Wheel Gap, Mineral County, is a filled-fissure vein about 3 feet wide occurring in volcanic ash (rhyolite tuffs and breccias). A very interesting feature of this deposit is the issuance of hot springs from the same fissure. Barite and calcite and some metallic sulfides occur as gangue minerals, and small amounts of these substances are being deposited by the hot springs.

New Mexico Fluorite Deposits.—New Mexico has several deposits of fluorite. They are scattered over five counties in the southwestern part of the state. The main production comes from Donna Ana County.

A deposit 10 miles north of Deming in Luna County has been worked for many years. The veins of this deposit dip steeply and cut a monzonite porphyry. They range from 2 to 12 feet in width and consist of massive fluorite. Quartz is the chief gangue mineral. Other deposits are in Grant, Sierra, and Socorro counties.

Miscellaneous Occurrences of Fluorite.—Deposits of fluorite occur in the Castle Dome district (Yuma County), in Pima County (25 miles southwest of Tucson), and at Aguila, (Yavapai County), *Arizona*; near Beatly, Nye County, *Nevada*; near Westmoreland, Cheshire County, *New Hampshire*; in *Tennessee*; in Toole County, *Utah*; and in Ferry, County, *Washington*.

Uses of Fluorite. *Metallurgical Uses.*—The chief use of fluorite, as has already been noted, is for metallurgical purposes, of which the making of steel by the basic open-hearth process (see description under Iron) is the most important. About 80 per cent of the annual production in the United States is used for metallurgical purposes.

The fluorite gives fluidity to the slag and aids in removing sulfur and phosphorus. In general, the average amount of fluorite used in producing 1 ton of steel is 7 or 8 pounds, but practice varies, and the quantity ranges from 2 to 25 or 30 pounds. Gravel fluorite that has passed through a 1-inch-mesh screen is generally used. Its average composition is shown by Table 112. Very little fluorite is used in foundries. A limited

amount is employed in refining gold, lead, copper, and antimony and in extracting aluminum from bauxite.

Use in Glass Making.—Glass makers use fluorite to make opalescent, opal, opaque, and colored glass. These glasses are used for lamp globes and shades, light bulbs, soda fountains, containers for toilet and medicinal preparations, bars and rods for lavatories, tableware, and novelties.

Use in Making Enamels.—From 3 to 4 per cent of our fluorite production is used in enamels for coating all sorts of kitchen and sanitary wares, plumbing fixtures, stoves, refrigerators, table and counter tops, reflectors, signs, facing for brick and tile, art pottery, structural materials, earthen cooking ware, and similar products.

Chemical Uses.—Only very pure fluorite is used for making hydrofluoric acid. Fluorite has also a few minor chemical uses. A small quantity is employed as a bond in making emery wheels and artificial abrasives.

Production of Fluorite in the United States.—The production of fluorite in the United States from 1880 to 1928 is shown in Fig. 236.

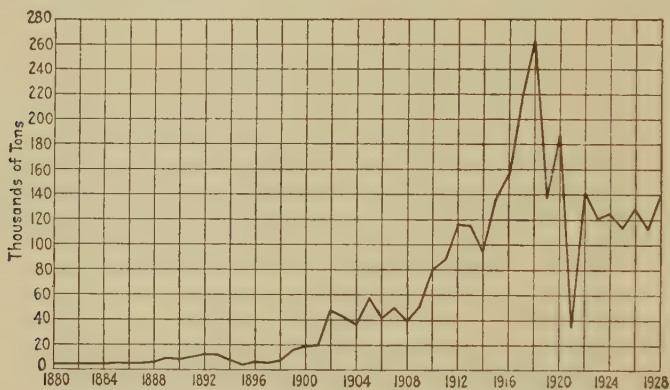


FIG. 236—Curve showing the production of fluorite in the United States from 1880 to 1928. (Data from U. S. Bur. Mines.)

This curve indicates the rapid rise in production after the discovery of the metallurgical use of fluorite in 1899. High duties on fluorite have considerably curtailed imports, although in 1928 about 47,000 tons of foreign fluorite (chiefly from England) was used by manufacturers along the Atlantic seaboard.

CRYOLITE

There are no deposits of cryolite in the United States; in fact, the only producing locality of cryolite in the world is at Ivigtut, Greenland. Greenland's entire production goes to Denmark and the United States.

Composition and Physical Properties of Cryolite.—Cryolite is a sodium aluminum fluoride, Na_3AlF_6 . The mineral is soft (2.5 to 3) and

brittle. Cryolite may be colorless, in which case it is translucent and when placed in water is nearly invisible because its index of refraction is nearly the same as that of water. Cryolite may be white and if so has a waxy luster.

Mode of Occurrence of Cryolite.—Cryolite occurs in compact, granular, or cleavable masses; more rarely, in crystals.

The Greenland Deposit.—The Greenland deposit of cryolite is in a small area of granite enclosed in an older granite gneiss. A pegmatite dike lies along one side of the deposit and is believed to be genetically connected with the cryolite. The deposit is irregular in shape and is about 100 by 500 feet on the surface. It is believed to increase in size downward.

The cryolite contains pyrite, galena, siderite, sphalerite, chalcopyrite, and fluorite. After mining, it is sorted into two grades: the material containing fluorite and the other minerals, and the pure cryolite. The deposit is worked throughout the year, but shipping is done only in summer.

Uses of Cryolite.—The major use of cryolite is in the smelting of aluminum, of which it was once the chief source. Cryolite is the solvent for alumina in the bath used in the electrolytic smelting of aluminum ores. Because of its high price (\$80 or more per ton), artificial cryolite made from fluorite is being substituted, but it is necessary to use some of the natural mineral in the bath. The other important use of cryolite is in making opalescent and white glass.

Distribution of the Cryolite Production.—The United States imports 30 per cent of the cryolite production, but a part of this is reexported to Canada. Our imports in 1927 amounted to 5,064 long tons, valued at \$410,876. This was a decrease of more than 4,500 tons from the 1925 importation, a decline which was probably due to the increase in the price demanded by the producers and the resulting substitution of the artificial cryolite. The fact that the aluminum production in the United States increased over 3,000,000 pounds during this time shows that the decline was not due to a decrease in the production of aluminum. Undue raising of a price rarely pays.

The rest of the Greenland cryolite production (70 per cent) goes to Denmark, whence it is distributed to manufacturers in the rest of the world.

Selected Readings on Fluorite and Cryolite

- BAIN, H. F.: The Fluorspar Deposits of Southern Illinois, *U. S. Geol. Survey Bull.* 255, 1905.
- CURRIER, L. W.: Fluorspar Deposits of Kentucky, Ky. *Geol. Survey Bull.* 13, 1923.
- DAVIS, H. W.: *U. S. Mineral Resources*, 1925, Part 2, pp. 7–24; 1926, Part 2, pp. 17–49. Good account of history of production and uses.
- FAY, A. H.: The Illinois-Kentucky Fluorspar Industry, *Eng. and Min. Jour. Press*, July 31, 1926.

- LADOO, R. B.: "Non-Metallic Minerals," pp. 223-230 (fluorite); pp. 176-180 (cryolite), McGraw-Hill Book Company, Inc., New York, 1925.
- : Fluorspar Mining, Milling, and Utilization, U. S. Bur. Mines *Bull.* 24, 1927.
- RIES, H.: "Economic Geology," pp. 327-334, John Wiley & Sons, Inc., New York, 1925.
- SPURR, J. E.: The Kentucky-Illinois District, *Eng. and Min. Jour. Press*, Oct. 30, Nov. 6, 1926.
- WELLER, Stuart.: Ill. State Geol. Survey *Bull.* 41, 1920.
- See, also, *Mineral Industry*.

CALCIUM CHLORIDE, MAGNESIUM CHLORIDE, AND BROMINE

Calcium and magnesium chloride and bromine are produced from the same brines and are, therefore, grouped together here. The production of calcium chloride, CaCl_2 , exceeds that of magnesium chloride, MgCl_2 , in the United States, and past practice has been to indicate the production of both as "calcium chloride." Magnesium chloride, however, having a purity of 97 per cent is now put on the market in large quantities, and its production is noted separately. Bromine occurs in the same brines, probably as MgBr_2 .

Calcium and magnesium chlorides and bromine occur as constituents of natural brines in Michigan, Ohio, and West Virginia and of the bitterns obtained in salt production in California (at Amboy, San Bernardino County; Mount Eden, Alameda County; and at Arden and Chula Vista).

Composition of the Brines.—Brines of the Marshall sandstone (Mississippian) in the Saginaw Valley (Saginaw County), Michigan, contain 0.14 to 1.62 per cent bromine. Brines of southeastern Ohio (Meigs County) and West Virginia (Mason County) contain about 0.32 per cent bromine. The following analysis of a brine from Meigs County, Ohio, illustrates the composition of these brines:

TABLE 113.—PARTIAL ANALYSIS OF A NATURAL BRINE FROM POMEROY, MEIGS COUNTY, OHIO¹

Compounds	Grams per liter
Sodium chloride, NaCl	84.300
Calcium chloride, CaCl_2	14.340
Magnesium chloride, MgCl_2	5.500
Barium chloride, BaCl_2	0.343
Strontium chloride, SrCl_2	0.257
Potassium chloride, KCl	0.114
Magnesium bromide, MgBr_2	0.155
Sodium iodide, NaI	0.004
Ferric oxide, Fe_2O_3	Trace
Aluminum oxide, Al_2O_3	Trace

¹ BOWNOCKER, J. A., Ohio Geol. Survey, vol. VIII, p. 27, 1906.

Method of Obtaining the Compounds from the Brines.—After the salt, NaCl , has been removed from the brines, the very soluble calcium

and magnesium compounds and the bromine remain in the bitters (mother liquors) which are then treated to remove them.

Uses of Calcium and Magnesium Chloride and Bromine.—*Calcium chloride* is used for laying dust (by absorbing moisture from the air); to prevent solutions from freezing; as protection against fire; as a wood preservative (for ties and fence posts); in making pigments and wall plaster; in tempering steel; in canning vegetables; in drying vegetables and fruits; as a deodorizer and a drying agent; and in numerous chemicals.

Bromine, in the form of potassium and sodium bromides and other salts, is used largely for medicinal and photographic purposes. It is also used in making certain aniline dyes; as a disinfectant; in chemical work; and, to a lesser extent, in metallurgical work. In recent years, a part of the marked increase in bromine production has been due to the use of bromine in making tetraethyl lead, which is employed in special "antiknock" gasolines.

Magnesium chloride is an important source of magnesium. The larger part of its production is put on the market as "flake chloride," but a part is sold in liquid form and used to lay dust on roads.

Production in the United States.—A very small production of the calcium and magnesium compounds and bromine was made in the United States before the World War. Since then, however, it has risen steadily. The production of calcium and magnesium chlorides in 1916 was 27,700 tons, valued at \$225,000; and in 1928 it was 102,000 tons, valued at \$1,995,000. These amounts do not include the large amounts of calcium chloride produced as a by-product in soda plants. Over 45,000,000 pounds of flake magnesium chloride was sold in 1926, and nearly 7,000,000 pounds of the salt in liquid form. The bromine production rose from 728,500 pounds in 1916 to 2,164,000 pounds in 1928.

Selected Readings on Calcium Chloride, Magnesium Chloride, and Bromine

PHALEN, C. W.: *Technology of Salt Making in the United States*, U. S. Bur. Mines Bull. 146, 1917.

RIES, H.: "Economic Geology," pp. 229, 230, John Wiley & Sons, Inc., New York, 1925.

BARITE

The value of barite as an economic product is based upon three important properties which it possesses: *inertness, stability, and weight*. For a long time, barite was used as a filler to give weight to other materials; in some cases, merely as an adulterant. It could be purchased for a few cents per pound and returned an excellent profit when used in lighter materials that sold by weight at a higher price. In some materials, its use was legitimate because of the stability of the barite. In paints, it was long regarded as an adulterant (it reduced the amounts of white lead or zinc oxide used), but fair tests have proved that the stability

and inertness of the barite add to the life of the paint. Barite has, therefore, come into its own as a valuable constituent of paints. Its opaqueness is also an asset, as barite paints are whiter than those made from most other pigments.

Composition of Barite.—Barite is barium sulfate, BaSO_4 , and nearly all of the material is pure. Strontium sulfate, SrSO_4 , is the most common impurity, where any is present.

Physical Properties of Barite.—Barite is normally white and opaque, but it may be yellow, red, gray, black, and other colors. Crystals of it may be colorless and transparent. The transparent varieties are not suitable for pigments but may be used for chemicals. The hardness of barite is from 2.5 to 3.5, and the specific gravity, from 4.3 to 4.6. Barite has two perfect cleavages, and a third that is less perfect. The



FIG. 237.—Barite nodules, near Potosi, Washington County, Missouri. (Photograph by W. A. Tarr.)

mineral occurs most commonly as nodules (Fig. 237) which are usually aggregates of thin tabular crystals, but it may be finely granular. Vein barite has a similar crystalline character; the tendency of the blades of the barite in this form to aggregate into nodular masses is shown by the larger mammillated surfaces. Barite has a fusibility of $1,580^{\circ}\text{C}$. It is very insoluble in water and only slightly soluble in acids. This insolubility is evidenced by the occurrence of barite as a residual mineral and by the fact that the iron stain, so common on the residual barite, is removed by boiling the finely ground barite in a dilute sulfuric acid solution.

Mode of Occurrence of Barite.—Barite occurs as beds, veins (Fig. 238), and irregular masses in limestone, dolomite, sandstone, and nearly all other kinds of rocks; as residual deposits (Fig. 238); as nodules in sandstones and shales; as individual crystals in various rocks; and as a gangue mineral in other mineral deposits.

Residual Deposits.—The major part of the barite production of the United States comes from residual deposits. The barite occurs in nodules or large nodular aggregates in residual clays. In most deposits, these clays are residual after limestone or dolomite and, to a lesser extent, after sandstones. The nodules may be scattered through the residual clay or may be in pockets that contain as much as 75,000 tons of barite. As a rule, the nodules occur at the bottom of the clay, usually within 30 or 40 feet of the surface.

Veins and Beds.—Veins and bedded deposits do not furnish much barite in the United States, but they are important abroad. Germany and England have excellent deposits of both types.

Barite as a Gangue Mineral.—Where occurring as a gangue mineral, barite is rarely of value, unless it occurs in such a way that it may be concentrated as a by-product.

Origin of Barite.—A difference of opinion still exists as to the origin of barite deposits. The early writers on the subject held the view that small quantities of barium in the surrounding rocks were concentrated by ground waters during weathering and thus formed the nodules and other aggregates of barite in the clay or the underlying limestones and dolomites. Against this view there are numerous arguments the chief of which are the insolubility of the common barium salts (the sulfate and the carbonate), the resulting difficulty of their transportation by ground waters, and the very fundamental fact that the associated rocks contain no (or *very little*) barium. One part of barium sulfate is soluble in 400,000 parts of water, and the carbonate is nearly as insoluble. Limestones and dolomites (the chief rocks which contain barite deposits) are devoid of barium. A composite analysis by Clarke¹ of 345 limestones shows none. Clarke² gives also a composite analysis of 253 sandstones which shows 0.05 per cent BaO, and such an analysis of 78 shales which shows between 0.04 and 0.06 per cent. This lack of a source of barium and the insolubility of barium compounds are strongly opposed to the view that barite is concentrated locally. Further evidence against the view is the common occurrence of large veins of barite (nearly 75 feet across) in igneous and metamorphic rocks. Such barite is undoubtedly of magmatic origin. Likewise, the extreme commonness of barite as a gangue mineral (in some places so abundant as to be workable) is another

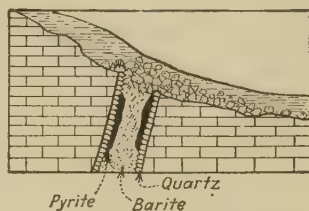


FIG. 238.—An ideal sketch of a barite vein (with quartz and pyrite as gangue minerals) in limestone, and the residual barite in the clay resulting from the weathering of the limestone. The barite works down the slope with the clay. These are the two common modes of occurrence of barite.

¹ CLARKE, F. W., Data of Geochemistry, U. S. Geol. Survey Bull. 491, p. 533.

² —, idem, p. 517.

proof that much barite is of magmatic origin, and it proves that barium could be transported in magmatic solutions. Barite would be deposited whenever the sulfate ion became sufficiently concentrated as a result of oxidation.

In at least two important deposits of barite, those of Missouri and Kentucky (and probably others of the southern Appalachian area), the evidence points undoubtedly to a magmatic source for the barite. The primary deposits in Missouri are typical fissure-vein and solution-cavity deposits. The veins show banding and crustification and a definite sequence in the deposition of the minerals. The minerals, in the order of deposition, are quartz (usually a layer of quartz alternates with chalcedony), pyrite, galena and sphalerite (not always present), and barite. The residual barite can be traced directly to these veins. The Kentucky deposits (and others of the southern Appalachian area) are associated with fractured and faulted zones. Barite veins are common in most of these occurrences, but only the residual concentrations are worked.

Barite Deposits in the United States.—Deposits of barite are widely scattered throughout the United States, but relatively few of them are workable under present conditions. The major production of barite comes from Missouri and Georgia (86 per cent in 1927). Deposits occur throughout the Appalachian Mountains and in the western part of the United States (see Fig. 239).

Missouri.—The Missouri barite deposits are found largely in Washington County but also in the adjacent counties of Jefferson and Franklin. Other districts producing some barite are the central district in Moniteau, Morgan, Miller, and Cole counties; and the southwestern district in Hickory County.

The barite in the *Washington County area* occurs in the Cambrian dolomite and in the clay residual from the dolomite. It occurs as veins along fissures, as irregular bodies in solution cavities, as disseminated grains and nodules, and as residual deposits. It is from the residual deposits that the production is made. The residual barite is found from the surface to depths of 18 to 20 feet. It occurs in a red clay and is mixed with chert, quartz, limonite, and rarely galena.

The deposits in the *central district* are usually associated with sink holes, where the barite is residual or occurs as a cementing material between the blocks of country rock filling the sink holes.

Georgia.—The Georgia barite deposits are second in value to the Missouri deposits. They occur near Cartersville, Bartow County, and near Elton, Murray County. Essentially all the production comes from the deposits east of Cartersville. The barite occurs entirely as residual deposits. It forms masses and nodules in clay over both the Beaver limestone and the Weisner quartzite (base of the Cambrian), and it occurs

with iron ore and ocher in fractures and cavities in the Weisner quartzite. The rocks are intensely folded and faulted. The main barite deposits lie along the east side of an anticline in which the beds dip 45° east.

Tennessee.—The Tennessee barite deposits are found in the Sweet-water district in McMinn, Monroe, and Loudon counties. The barite occurs as residual deposits over the Knox dolomite. Chert and limonite are common gangue minerals. The residual clays attain thicknesses of 60 feet, but most of the barite comes from clay 10 to 20 feet thick. The rocks of the region are much folded and faulted.

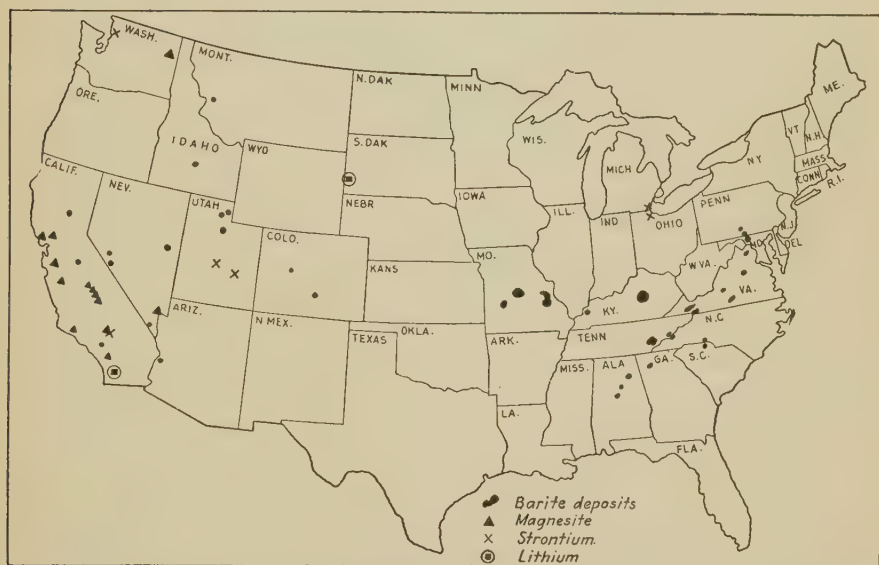


Fig. 239.—Map showing the barite, magnesite, strontium, and lithium deposits in the United States. (Data from *U. S. Mineral Resources and other sources.*)

Kentucky.—Kentucky has some important barite deposits in the vicinity of Lexington. They are distinctly of the vein type and occur mainly in Ordovician rocks. They are principally associated with limestones. Numerous gangue minerals occur in the veins. In western Kentucky, barite occurs in veins associated with the fluorite deposits.

Other States.—Barite is also found in Alabama, Arizona, Alaska, California, Idaho, Montana, Nevada, North Carolina, South Carolina, Utah, Virginia, and Wisconsin. In nearly all these states, the deposits are veins yielding barite of a very high grade. The country rocks are igneous, metamorphic, and sedimentary.

Uses of Barite.—Three major products are made from barite, as the following table shows:

TABLE 114.—CRUDE BARITE (DOMESTIC AND IMPORTED) USED IN THE MANUFACTURE OF THE MAJOR BARIUM PRODUCTS IN THE UNITED STATES, 1928¹

Product	Short tons	Percentage of total amount used
Lithopone.....	228,617	71.3
Ground barite.....	59,953	18.7
Barium chemicals.....	32,041	10
Totals.....	320,611	100.0

¹ U. S. Mineral Resources, 1928, Part 2, p. A 16.

Lithopone has already been discussed under Mineral Paints (p. 525). It is a pigment composed of 70 per cent barium sulfate and 30 per cent zinc sulfide and zinc oxide. In addition to its use as a pigment, it is employed as a filler for various high-grade rubber goods; in oilcloth, linoleum, and, to a lesser extent, in printer's ink and face powder; and for other uses.

Ground barite is used as an inert filler in paints; it is employed in rubber, linoleum, cloth, paper, oilcloth, and other products. It makes an excellent surface and therefore is used on playing cards, bristol board, enameled paper, and other surfaced papers. It is used in making artificial ivory for buttons and poker chips; as a base for lake because finely divided barite can absorb large amounts of colored pigments; in making glazes and enamels; in tanning; and in making numerous other minor products. In the manufacture of gorgonzola cheese in Italy, a heavy coating of finely ground barite is employed for protection from the air. Much ground barite is sold to chemical manufacturers for uses where inertness and weight are desired. Finely ground barite is extensively used for making a heavy fluid used in drilling rotary holes and in controlling high gas pressures. The finely divided barite (it must pass a 200- or 300-mesh screen) remains in suspension in the water a long time, adding to the weight of the water and therefore helping to check the gas flow.

Barium chemicals include a long list of salts that find an extraordinarily large number of uses in industrial processes and in the chemistry laboratory.

The chief of these chemicals is artificial barium sulfate (*blanc fixe*), and the next is barium carbonate. The sulfate is used where an especially high-grade product is needed. The carbonate is used in making optical glass and in enamels for iron and steel ware (so-called "granite ware"), as it gives the enamel a luster and density as high and a fusibility as low as does lead, and it is not poisonous. The carbonate is used also in paints. A paint having 45 per cent precipitated barium carbonate gives a velvety finish as a flat wall paint.

Other barium chemicals are the nitrate, chloride, sulfide, chromate, and hydroxide.

Production of Barite in the United States.—The production of crude barite in the United States in 1928 was 269,544 tons, valued at \$1,750,709. Over 61,000 tons was imported that year, valued at \$190,000. Figure 240 shows the production of barite in the United States from 1883 to 1928.

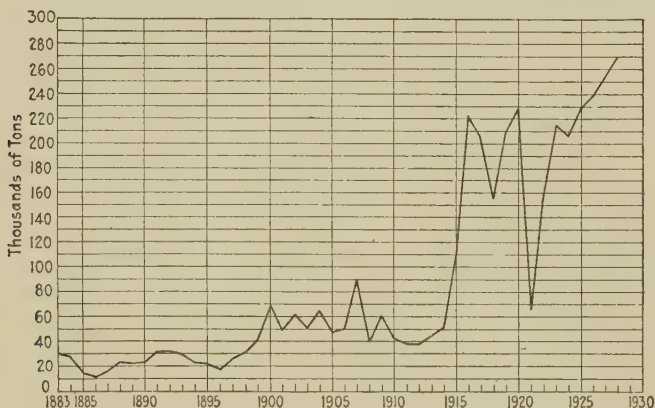


FIG. 240.—Production of barite from 1883 to 1928. Compare with Fig. 218 for lithopone. (Data from U. S. Mineral Resources.)

Selected Readings on Barite

- HILL, J. M.: Barytes and Strontium, *U. S. Mineral Resources*, 1915, Part 2, pp. 161–187.
- HULL, J. P. D.: Report on the Barytes Deposits of Georgia, Ga. Geol. Survey. *Bull.* 36, 1920.
- LADOO, R. B.: “Non-Metallic Minerals,” pp. 67–80, McGraw-Hill Book Company, Inc., New York, 1925.
- LINDGREN, WALDEMAR: “Mineral Deposits,” pp. 441–445, McGraw-Hill Book Company, Inc., New York, 1928.
- RIES, H.: “Economic Geology,” pp. 309–318, John Wiley & Sons, Inc., New York, 1925.
- SPENCE, H. S.: Barium and Strontium in Canada, Can. Dept. Mine sBranch *Bull.* 570, 1922.
- TARR, W. A.: The Barite Deposits of Missouri and the Geology of the Barite District, Univ. Mo. *Studies*, vol. III, No. 1, 1917.
- See, also, *U. S. Mineral Resources* and *Mineral Industry*.

MAGNESITE AND DOLOMITE

Magnesite has always been the important source of magnesia. Until 1914, the United States imported the greater part of the magnesite used; but, when the foreign supplies were cut off during the World War, the development of domestic deposits was pushed. The production of magnesite rose from 9,600 tons in 1913 to 316,800 tons in 1917, in spite of the fact that the price increase was only \$1.15 per ton and producers had thought it impossible to produce the material here at a price so low. Dolomite is discussed in connection with magnesite, as it, also, is now an important refractory and source of magnesia.

MAGNESITE

Composition of Magnesite.—Magnesite is magnesium carbonate, MgCO_3 , containing 47.6 per cent MgO and 52.4 per cent CO_2 . Both ferrous and ferric oxides may be present, the former up to 8 or 10 per cent, and the latter in sufficient amounts to give a brown color to the magnesite, which is then called "brown spar." Other compounds commonly present are CaO , Al_2O_3 , SiO_2 , and H_2O (in iron oxides). The iron in magnesite is of value when the material is used for refractory purposes.

Physical Properties of Magnesite.—There are two forms of magnesite: the crystalline and the cryptocrystalline (commonly called "amorphous"). Crystalline magnesite occurs as coarse crystals most of which are less than $\frac{1}{2}$ inch in diameter, but some of which are 3 inches. The cryptocrystalline variety has a dense porcelainous texture and a curved or conchoidal fracture. This variety is thought to be a hardened colloidal gel. Most of the amorphous magnesite is pure white, but some is yellowish white. The crystalline variety is yellowish or brownish white but may also be pure white. Most magnesite is opaque, but some is transparent. Magnesite has a hardness of 3.5 to 4.5, is brittle, and has a specific gravity of 3.0 to 3.12. There is no agreement as to the temperature at which it loses its carbon dioxide. Figures given range from 510 to 700°C., and even higher temperatures are said to be employed in calcining the material. To dead burn magnesite completely, temperatures of 1,800 to 1,900°C. are said to be necessary, yet, according to Palmer,¹ the temperature used for dead burning magnesite in California is 1,550°C. Magnesia, MgO , does not melt until 2,800°C. is reached, but it softens at a lower temperature.

Mode of Occurrence of Magnesite.—There are three common modes of occurrence of magnesite: (1) *as veins in serpentine*; (2) *as replacements of dolomite or limestone*; and (3) *as a sedimentary rock*.

Veins in Serpentine.—A widespread occurrence of magnesite is that of the so-called "amorphous" form as veins in serpentine. These veins vary much in size and run in all directions through the serpentine, forming a network (Fig. 241). The magnesite deposits in California and in Greece are of this type.

Replacements of Dolomite or Limestone.—The crystalline variety of magnesite is commonly the result of magnesia-bearing solutions' having altered a dolomite or limestone. The magnesite occurs as great masses, which are usually lenticular but are also more or less irregular. These masses are associated with the carbonate rocks and other sediments. Some of them are of enormous size. The magnesite resembles marble, and attempts have been made to quarry it and substitute it for marble.

¹ PALMER, L. A., Magnesite Mining in California, Am. Inst. Min. and Met. Eng. Bull. 1629-H, p. 11, 1927.

The large magnesite deposits of Washington, Austria, Czechoslovakia, and Quebec are of this type.

Magnesite as a Sedimentary Rock.—The occurrence of magnesite as a sedimentary rock is a rather recent discovery. The mineral occurs in beds whose maximum thickness is 200 feet. The magnesite is the cryptocrystalline variety. It is pure white, dense, massive, and is softer than the vein magnesite.

Origin of Magnesite.—Each of the three types of magnesite deposits represents a different mode of origin. The *amorphous variety* is the result of the action of carbonate waters upon the magnesium silicate of the serpentine. The silica freed in the process is deposited as chalcedony and quartz. The *crystalline magnesite* resulted where a solution bearing magnesia, MgO , entered a carbonate rock and replaced the CaO . Dolomite is believed to have been more common as the original rock than limestone. The common presence of more iron in this type of magnesite deposit is in keeping with this view, as ferrous iron normally replaces some of the MgO in dolomite and is not so common in limestones. The source of the magnesia-bearing solution was evidently an igneous rock. *Sedimentary magnesite* is relatively rare. The known deposits are associated with other sedimentary strata of Tertiary age. The solution depositing the magnesite apparently occurred in a closed basin, where the mineral was deposited after a reaction with sodium carbonate had taken place.

Magnesite Deposits in the United States.—Important deposits of magnesite are found in only three states: California, Nevada, and Washington; and only California and Washington are at present (1928) productive (see Fig. 239, p. 581).

California.—The magnesite deposits of California occur in the coast ranges from Riverside County to Mendocino County and on the west slope of the Sierra Nevadas in Tulare and Fresno counties. A deposit in Kern County is apparently of the sedimentary type, but essentially all the others are the amorphous-vein type. The magnesite is very pure and is used more extensively for calcining than is the Washington product. The veins which are worked range from 2 to 24 feet in width



FIG. 241.—Stockwork of magnesite veins in serpentine (white areas), 3.5 miles south of Winchester, Riverside County, California. (After Hess, U. S. Geol. Survey Bull. 355, pl. 8-A, p. 38.)

and are mined by open-cut and underground methods. After mining, the material is sorted and prepared for burning, as little California magnesite is sold in the crude form.

Washington.—A crystalline magnesite deposit was discovered in 1916 in Stevens County, Washington. It occurs in a narrow belt, about 22 miles long, that strikes southwest from a point about 5 miles west of Chewelah. The magnesite occurs as replacement lenses, which reach a quarter of a mile in length and are from a few to 300 feet in thickness. It ranges from fine to coarse grained and is gray, white, black, pink, or red. The original dolomite is partially or in some places entirely replaced. Basic igneous rocks occur in the sedimentary series, both above and below the magnesite, but none is in contact with it. The reserves of magnesite are large; some properties have over 1,000,000 tons within 100 feet of the surface. The deposits are favorably located for mining and transportation. The mineral is rather low in iron for a magnesite of the crystalline type, and iron is added to improve its value for refractory linings of furnaces, which is the use to which the greater part of the production is put.

Nevada.—A deposit of sedimentary magnesite occurs in Clarke County, Nevada, in the valley of Muddy River a few miles above the town of St. Thomas. The rock was formerly called "kaolin," and a limited amount was used as such. The material is pure white and occurs in a bed 200 feet thick in places. The magnesite is interbedded with other sedimentary rocks. An exposure of the rock extends as a bluff along the Muddy River for nearly a mile. The magnesite resembles the amorphous variety but crumbles more readily on exposure. The deposit has not been worked much, but it is large and readily accessible and thus constitutes an important reserve.

Foreign Magnesite Deposits.—Very important foreign magnesite deposits occur in *Quebec, Austria, Czechoslovakia, Greece, India, Manchuria, Venezuela*, and several other countries. Austria and Czechoslovakia contain the largest deposits known. For years, the European countries were the main source of the magnesite imports into the United States.

Uses of Magnesite.—The three types of magnesite products marketed are, in the order of their importance: (1) *dead-burned magnesite*; (2) *caustic calcined magnesite*; and (3) *crude magnesite*.

The *dead-burned material* is a splendid basic refractory and finds its largest use in the linings of basic open-hearth steel furnaces and converters. It is also used in numerous other furnaces and kilns (Portland-cement kilns, for example), where a highly resistant refractory is needed. The material is used in the grained form or is made into brick (the iron content is valuable as a bond in making brick). The dead-burned product contains no carbon dioxide.

Caustic calcined magnesite contains from 2 to 5 per cent carbon dioxide. In producing it, the magnesite is burned at a lower temperature (about 1,200°C.) than that at which the dead-burned product is produced. Its great value lies in making a long series of strong, quick-setting cements of which magnesium oxychloride (or sorel) cement is an example. This cement is made by adding to the finely ground caustic magnesite a solution of magnesium chloride obtained from brines. The cement is plastic; sets hard; and is dense, tough, and elastic. It can be drilled, planed, scraped, and burnished like wood and is widely used for flooring in railroad cars, hospitals, offices, kitchens, and on ships. It can be used on walls and makes an excellent stucco for exterior use. Coloring agents and fillers of all sorts are added to the cement for special purposes. Because of its quick-setting property, it can be used at freezing temperatures.

Crude magnesite has many uses. Formerly, it was employed in the sulfite process of making paper, but not very much is so utilized at present. It was once used as a source of carbon dioxide, but this use, also, is much less now. Various magnesium salts (Epsom salts, for example) are made from either crude magnesite or the calcined product.

All three of the products have a series of minor uses of which the following are a few: in making face powder, disinfectants, cotton fabrics, various dryers, fertilizers, and deodorizers; and in sugar refining, heat insulation, photography, and pyrotechnics.

Production of Magnesite in the United States.—The total production of magnesite in the United States in 1928 was 127,200 tons, of which 85,900 was produced in Washington and 41,300 in California. The same year, 63,500 tons was imported. The domestic production of magnesite in 1928 was distributed as follows among the three types of products:

TABLE 115.—MAGNESITE PRODUCTION OF THE UNITED STATES AND ITS VALUE, 1928¹

Product	Amount, tons	Value	Average value per ton
Crude magnesite.....	620	\$ 5,690	\$ 9.18
Caustic calcined magnesite.....	13,310	454,820	34.17
Dead-burned magnesite.....	45,230	1,076,310	23.80

¹ U. S. Mineral Resources, 1928, Part 2, p. 129.

DOLOMITE

Dolomite is used largely for the same purposes as limestone, but it also has other applications that are dependent upon its magnesium content, and it is these that are discussed here in connection with magnesite.

Composition of Dolomite.—Dolomite is calcium-magnesium carbonate, (CaMg)CO₃. It contains 45.65 per cent MgCO₃ and 54.35 per

cent CaCO_3 or 21.7 per cent MgO , 30.4 per cent CaO , and 47.9 per cent CO_2 . Ferrous iron and manganese are present in many dolomites.

Physical Properties of Dolomite.—In form, dolomite occurs as single crystals and as massive crystalline rock masses. The crystals usually have curved faces. Dolomite is white, gray, pink, brown, and other

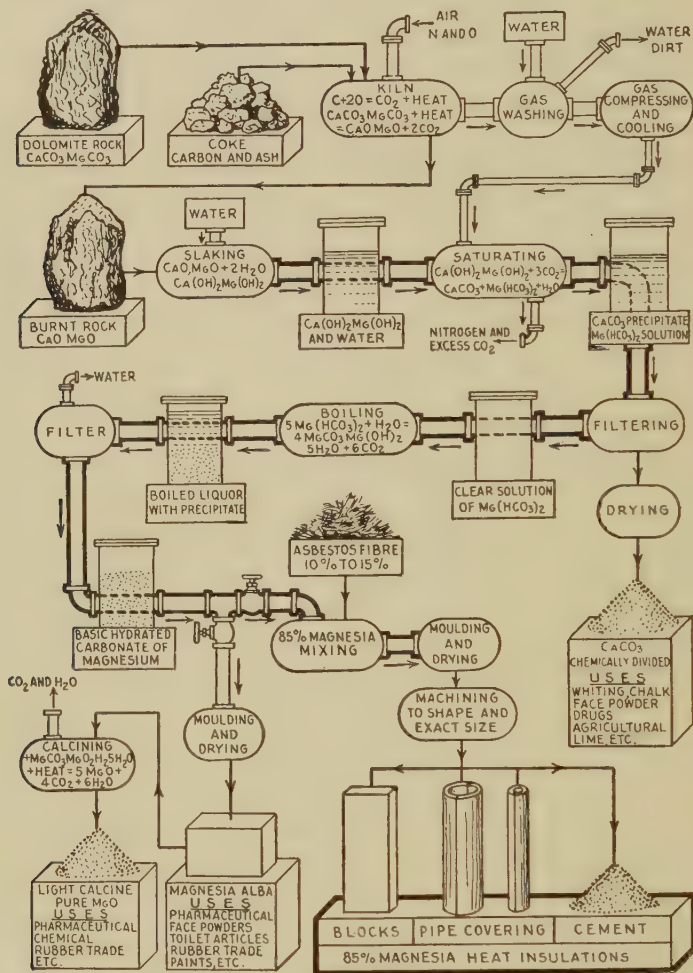


FIG. 242.—Flow chart illustrating manufacture of "85-per cent magnesia." The darkened lines show the actual process involved. The lighter lines, by-processes. (After Ladoo, "Non-Metallic Minerals," p. 205.)

shades. It has a hardness of 3.5 to 4 and a specific gravity of 2.8 to 2.9. The carbon dioxide is driven off at high temperatures (from 900°C . up). The resulting $\text{MgO} + \text{CaO}$ is infusible; hence its use in refractories.

Mode of Occurrence and Origin of Dolomite.—The occurrence of dolomite as a sedimentary rock is very common and well known. Some

dolomites are chemical precipitates, and others evidently resulted where magnesium carbonate reacted with some form of calcium carbonate already deposited to form the double salt.

Geologic Distribution of Dolomite.—Dolomite is as widespread as are sedimentary rocks, but it is most abundant in Paleozoic and pre-Cambrian formations.

Uses of Dolomite Depending on Its Magnesium Content.—The uses of dolomite which are based on its magnesium content are dominantly two: as a refractory and in making basic magnesium carbonate.

The value of dolomite as a refractory has long been known, but not much of it was so employed in the United States before 1914. During the World War, however, due to the limited amount of magnesite available, attempts were made to find a substitute for it. In 1917, 349,000 tons of dead-burned dolomite was used for refractory purposes in the United States, and, in 1928, 710,000 tons. Although the carbon dioxide of dolomite is driven off at $510^{\circ}\text{C}.$, it is necessary to heat it to $1,480$ or $1,700^{\circ}\text{C}.$ to produce a satisfactory dead-burned product. Before being used, however, the dead-burned material must be treated to prevent slaking. The material is used in granular form rather than in bricks.

Dolomite is used to make basic magnesium carbonate, $4\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2 \cdot 5\text{H}_2\text{O}$, which is mixed with 10 to 15 per cent asbestos fiber to make "85-per cent magnesia" pipe coverings for heat insulation. The process of doing this is shown in Fig. 242. Several by-products are obtained in making the basic carbonate. In 1928, 72,850 tons of dolomite was used for this purpose in the United States.

The possibility of using dolomite in oxychloride cement has been investigated considerably in recent years, but as yet the method has not been fully successful. This material would become a competitor of Portland cement if its process of manufacture could be carried on cheaply enough.

Selected Readings on Magnesite and Dolomite

- DOLMAN, C. D.: Magnesite, Its Geology, Products, and Their Uses, Am. Inst. Min. and Met. Eng., *Bull.* 152, pp. 1193–1202, 1919.
- HESS, F. L.: Magnesite Deposits of California, U. S. Geol. Survey *Bull.* 355, 1908.
- HILL, J. M.: *U. S. Mineral Resources*, 1925, Part 2, pp. 77–91; 1926, Part 2, pp. 127–140.
- LADOO, R. B.: "Non-Metallic Minerals," pp. 325–342 (magnesite); pp. 198–206 (dolomite), McGraw-Hill Book Company, Inc., New York, 1925. Contains bibliography.
- RIES, H.: "Economic Geology," pp. 355–362, John Wiley & Sons, Inc., New York, 1925. Contains bibliography.
- STONE, R. W.: Spurr's "Political and Commercial Geology," pp. 363–371, McGraw-Hill Book Company, Inc., New York, 1920.

LITHIUM MINERALS

Lithium is one of the alkali metals that has a series of minor uses. In the United States, the value of all lithium minerals produced is but a fraction of a per cent of the total mineral production.

The Lithium Minerals and Their Distribution and Production in the United States.—Lithium is obtained from three minerals, namely, *amblygonite* (a fluorophosphate of aluminum and lithium), *lepidolite* (lithia mica), and *spodumene* (a lithium-aluminum silicate). All these minerals occur in a deposit near Pala, San Diego County, California (see Fig. 239, p. 581). An abundance of tourmaline is present in the deposit, also. The tourmaline and a transparent variety of spodumene are the important products, both being prized as gems.

Spodumene is found in the pegmatite veins at the Etta Tin mine, Pennington County, *South Dakota* (Fig. 239). It occurs in crystals, some of which attain the remarkable length of 40 feet and weigh 35 to 40 tons (Fig. 16, p. 46). Lithium minerals are found in other localities, also, but their production is confined to *South Dakota* and *California*. The production of lithium minerals in the United States in 1928 was 4,600 tons, valued at \$94,750.

Uses of Lithium.—Important uses of lithium, in the form of several lithium salts, are for pharmaceutical preparations and in making fireworks and signal rockets. Its use for the latter purposes depends upon the fact that lithium colors a flame deep red. Lithium hydroxide, LiOH , is a constituent of the electrolyte in the Edison storage battery. The bromide and iodide of lithium are used in photography. A recently developed use of the metal and one which requires large amounts of lepidolite is in making opal and white glass and also flint glass. The following table shows the composition of a typical opal-glass batch, as given by Ladoo. The table is of interest in showing the raw materials that go into a special glass.

TABLE 116.—COMPOSITION OF AN OPAL-GLASS BATCH¹

Constituents	Amount, pounds
Sand.....	2,000
Soda.....	750
Lime (burned).....	40
Feldspar.....	240
Fluorite.....	1,580
Lepidolite.....	1,420
Arsenic.....	10
Color.....	0.625

¹ LADOO, R. B., "Non-Metallic Minerals," p. 322.

Selected Readings on Lithium Minerals

LADOO, R. B.: "Non-Metallic Minerals," pp. 319-322, McGraw-Hill Book Company, Inc., New York, 1925.

STRONTIUM MINERALS

Although the United States contains large deposits of strontium ore, none has been produced since 1918. The demand for strontium salts is small, and they are cheap; so, as the best deposits of the ore in the United States are relatively inaccessible, all strontium salts are imported.

The Strontium Minerals and Their Mode of Occurrence.—Strontium is obtained from two minerals: *celestite*, SrSO_4 , the most important source; and *strontianite*, SrCO_3 . These minerals occur *as constituents of vein deposits* (especially with barite, galena, and calcite); *as disseminated crystals in limestone and dolomite*; and *in solution cavities in dolomitic limestones*.

Distribution of Strontium Minerals in the United States.—The largest deposits of strontium minerals in the United States occur in *California*, in association with salt and gypsum and other sediments which have apparently been formed in old lakes. In one of these deposits in the Avawatz Mountains, San Bernardino County, the celestite zone has a maximum thickness of 80 feet. Strontium deposits occur, also, in *Utah, Arizona, Texas, Washington, Michigan, New York, Ohio, and West Virginia* (see Fig. 239, p. 581).

Uses of Strontium.—The uses of strontium are entirely chemical. A great many strontium salts are employed in the chemical laboratory, and a few in certain industrial processes. Strontium hydrate is used in a special process of making beet sugar but only to a limited extent in the United States. Strontium nitrate imparts a brilliant red color to a flame and hence is used in all sorts of fireworks, rockets, and flares. Special applications of certain salts are common. Ground celestite has been substituted for barite as a filler, and attempts have been made to produce from it a paint similar to lithopone.

Selected Readings on Strontium Minerals

LADOO, R. B.: "Non-Metallic Minerals," pp. 592-599, McGraw-Hill Book Company, Inc., New York, 1925.

U. S. Mineral Resources and Mineral Industry have some notes of interest.

MONAZITE AND THORIUM

The chief value of monazite lies in the amount of the rare earth thorium which it contains. It is also the chief source of the rare earths of the cerium, lanthanum, neodymium, didymium, and praseodymium group; and of mesothorium, a radioactive element. These rare earths add to the value of monazite but not so much as does its thorium content. Thorium may be secured from other minerals, such as thorite and thorianite, but commercial deposits of these are very rare, and only a few contribute to the production of thoria, ThO_2 .

Composition of Monazite.—Monazite is a phosphate of the cerium metals. Its formula is $(\text{Ce, La, Di})\text{PO}_4$, but thoria is usually present,

also. The thoria content of monazite ranges from traces to 20 per cent, but for a monazite of commercial value it must exceed 5 per cent, and it usually lies between 5 and 10 per cent.

Physical Properties and Mode of Occurrence of Monazite.—Monazite is a hard (5 to 5.5), heavy (sp. gr. 4.9 to 5.3), and relatively insoluble mineral. It occurs as a *minor accessory mineral of granites and gneisses* and less commonly as fairly large masses in *pegmatite dikes*. These occurrences, however, do not furnish the monazite of commerce, which comes almost entirely from *gravels and sands*. Where monazite is liberated from the parent rock by weathering, it is concentrated in the soils and from them is further concentrated in alluvial deposits along streams or more rarely beaches. These monazite sands are not ores, but, on further concentration, they contain 80 or 90 per cent monazite and from 7 to 9 per cent thoria.

Monazite Deposits of the United States.—The United States formerly produced considerable monazite sand, but, aside from a single ton produced in 1925, there has been no production of it since 1918. All the monazite used is imported. About \$24,000 worth of monazite sand and \$14,100 worth of thorium nitrate were imported in 1928. The ton produced in 1925 came from Pablo Beach, Duval County, *Florida*.

The former productive area in the United States was a belt, 20 to 40 miles wide and 50 miles long, that extended from Wilkesboro, Wilkes County, *North Carolina*, to Anderson, Anderson County, *South Carolina*. These sands were not rich enough, however, to compete with the Brazilian deposits and production ceased many years ago. Monazite sands have been reported from *Idaho* (near Idaho City, Boise County), *Colorado*, *Oregon*, and *Washington*.

Foreign Monazite Deposits.—The productive deposits of monazite are in *Brazil*, *India*, and *Ceylon*. The monazite occurs as a sand of varying richness.

Uses of Monazite.—*Thoria* is used chiefly in making gas mantles. Metallic thorium, alloyed with tungsten, makes very ductile electric-light filaments.

Cerium, in the form of several salts, is used in ceramics; tanning; and in making medicine, optical glass, and electric-arc lamps. An alloy of metallic cerium (30 per cent) and iron (70 per cent) strikes fire when rubbed with steel and is extensively used for lighting inflammable gases in miners' carbide lamps, cigar lighters, and automatic gas lighters. A ton of monazite containing 5 per cent thoria will yield about 2.5 milligrams of mesothorium.

Selected Readings on Monazite and Thorium

JOHNSTONE, J. S.: "The Rare Earth Industry," pp. 3-28, London, 1915.

- LADOO, R. B.: "Non-Metallic Minerals," pp. 392-402, McGraw-Hill Book Company, Inc., New York, 1925. Contains bibliography.
- MOORE, R. B.: Spurr's "Political and Commercial Geology," pp. 216-222, McGraw-Hill Book Company, Inc., New York, 1920.
- RIES, H.: "Economic Geology," pp. 377-379, John Wiley & Sons, Inc., New York, 1925.
- SCHALLER, W. T.: Thorium, Zirconium, and Rare Earth Minerals, in 1919, *U. S. Mineral Resources*, 1919, Part 2, pp. 1-32.
- SCHLUNDT, H., Mesothorium, U. S. Bur. Mines *Tech. Paper* 265, 1922. Contains bibliography.

CHAPTER XVI

MATERIALS OF MISCELLANEOUS USES

INTRODUCTION

Man is always searching for new materials that may have some possible use and is seeking new uses for those already known. The great majority of earth materials possess some property that makes them useful; so, if they occur in sufficient abundance to be mined and are accessible, they soon find their way into the industrial world. In the course of progress, old industrial processes are often revised or discarded, and materials that will meet the new standards are required. So it often happens that a material which had long been known but was of no especial value finds a use. The recent utilization of andalusite as a refractory material is an illustration of this.

The materials grouped together in this chapter have widely varying uses; some are of minor importance, and substitutes for them could probably be readily found; others are indispensable. Mica, for example, has no equal for electrical-insulation purposes, in spite of all the attempts that have been made to find one. On the other hand, science has been able to match or even to improve on nature in her production of some materials, as in the case of abrasives and of graphite. The present efficient control of conditions in the laboratory and furnace makes possible the manufacture of these products on such a scale that competition with nature in quantity is possible, also. Demand creates values; and, as values go up, the possibilities of artificial products increase. Processes that at first were expensive undergo revision, and finally the artificial material is able to compete successfully with the natural product. Twenty-five years ago, \$100,000 worth of lithographic limestone was annually imported into the United States for the highest types of lithographic work, but substitutes were found for it, and in 1927 only \$6,690 worth was imported and none was produced at home.

The materials discussed in this chapter are of varying importance; but, for greater convenience, they will be arranged alphabetically, rather than in the order of their value. Those included are:

- Abrasives.
- Bentonite.
- Diaspore.
- Diatomaceous earth.
- Feldspar.

Fullers' earth.
Gems and semiprecious stones.
Graphite.
Mica.
Mineral fillers.
Pyrophyllite.
Quartz.
Refractories.
Sepiolite or meerschaum.
Talc (steatite) and soapstone.
Tripoli.

ABRASIVES

Any material that is sufficiently hard may be used as an abrasive. Preferably, the material should have a sharp edge suitable for cutting; but this is not necessary, for rounded grains of quartz sand are used in sawing and dressing stone and in sand blasting. Many naturally occurring materials are used as abrasives; some, as they are quarried; and others, after preparation.

Natural Abrasives.—Natural materials that require only dressing and shaping are *millstones*, *buhrstones*, *grindstones*, *scythestones*, *pulpstones*, *whetstones*, *oilstones*, *pumice*, *pebbles for grinding*, and *sand*.

Materials that must be ground and used either as grains or powder or molded into some form are *volcanic ash*, *diatomaceous earth*, *tripoli*, *quartz*, *feldspar*, *garnet*, *corundum*, *emery*, and *diamonds*.

Composition, Properties, Mode of Occurrence, and Distribution of Natural Abrasives.—*Materials Used for Grinding.*—*Millstones*, *buhrstones*, and *pulpstones* are stones of large diameter that are used for grinding paint pigments, cereals, cement rock, barite, fertilizers, wood, and other materials. They are usually composed of sandstone with sharp, angular grains that have good cutting edges. Certain siliceous limestones from *France* were for years imported into the United States for buhrstones. Steel grinding machinery (as well as artificial abrasives) is rapidly replacing this type of stone. *Pebbles and blocks for grinding* include chert or flint (largely imported for use in the United States from *France*, *Belgium*, and *Denmark*); beach pebbles of quartz and quartzite; and artificially rounded pebbles of quartzite from *Jasper*, *Minnesota*, and silicified rhyolite from *Manhattan*, *Nevada*. Quartzite used for lining ball and tube mills is quarried in *Minnesota* and *South Dakota*.

Materials Used for Sharpening.—Stones used for sharpening must have a very fine texture, be uniform in hardness, and have good cutting qualities; especially must this be true for fine grades of hones. Oil is used on these fine-grained stones because it fills the openings of the stone and, being viscous, prevents the entrance of the bits of metal removed in sharpening tools and instruments.

Grindstones and *scythestones* are usually composed of a fairly well-cemented sandstone the grains of which have sharp edges. The Berea grit of *Ohio* and *Michigan* is highly prized and widely used for such stones. Scythestones are also made from a schistose rock quarried at Evansville, Orleans County, *Vermont*, and Pike Station, Grafton County, *New Hampshire*. *Hones*, *whetstones*, and *oilstones* are made from very fine-grained sandstones, quartzites, mica schist, and novaculite. The famous whetstones called "Hindustan" or "Orange stone" are produced in Orange County, *Indiana*, and others called "Deerlick stone" come from Cuyahoga County, *Ohio*. The novaculite stone of *Arkansas* is a very fine-grained, siliceous rock (probably a chert) used for razor hones and stones for sharpening surgical instruments and drawing pens. It is quarried in Saline and Garland counties. The beds from which it is taken dip steeply, and large pieces are very difficult to secure because the rock is so badly fractured.

Materials Used for Scouring and Polishing.—Large pieces of *pumice* (a light, porous volcanic glass) are used for scouring and polishing purposes. *Arizona*, *New Mexico*, and *California* furnish the chief production of pumice in the United States, but more than twice the amount of their production is imported, chiefly from the island of *Lipari* in the Mediterranean. *Pumicite*, a fine, powdery volcanic ash, is produced in Meade, Norton, and other counties in *Kansas* and in Lincoln and other counties in *Nebraska*. In some beds, it is 30 feet thick and rarely even 100 feet. The beds worked are usually 6 to 10 feet thick and have different thicknesses of overburden. This material is wind-blown volcanic ash that came from volcanoes in the Rocky Mountain region. A harder material that has to be ground is produced in the Imperial Valley, *California*.

Materials that must be ground and used either in the granular or powdered form come from many sources. Such material may be used as grains or powder; mounted on cloth or paper (as sandpaper, garnet paper, and emery cloth); or mixed with a binder (see Fluorite, p. 754), molded into the desired form, and fired in a furnace until the binder fuses and makes a hard, resistant grinding stone. *Tripoli* is nearly pure silica and is mined in Newton County, *Missouri*, and Union County, *Illinois*. *Rottenstone* (produced in *Pennsylvania*) is the result of the leaching of an argillaceous rock and the concentration of the alumina and silica. The rock resembles tripoli but is unlike it chemically. *Garnets* are found in *New York* in Warren and Essex counties and in *North Carolina*. The garnets occur in gneisses and, to a lesser extent, in schist. Some of those in New York are 10 inches or more in diameter. About 95 per cent of the garnets produced are made into garnet paper or cloth, both of which are used in the woodworking and leather industries. Recently, attempts have been made to substitute garnet cloth for emery

paper in polishing plate glass. *Emery*, which is a mixture of corundum, magnetite or specularite, and spinel, has been produced in several places in the Appalachian region. Some of these localities are *New York* (Peekskill), *Virginia*, and *North Carolina*; but only New York makes a production at present (1929), and that is small. Practically all the emery used in the United States is imported from *Turkey* and *Greece*. *Corundum* (hardness 9) was formerly produced in the Carolinas, but all must now be imported. *Diatomaceous earth* (see Diatomaceous Earth, p. 602) is used to a certain extent in polishing and cleaning powders. The major production of it in the United States comes from *California*, but some comes from *Oregon*, *Washington*, *Nevada*, *New York*, and *New Hampshire*. *Diamond dust* is used for grinding and polishing gems. It is imported into the United States.

Materials Used for Cutting and Drilling.—Diamonds, the hardest minerals known, are used in many industries. It is said that the automobile industry is the largest user of industrial diamonds. The diamonds used industrially are *bort* (dark-colored, poorly crystallized, dense or fibrous, found in fragments) and *carbonado* or *black diamonds* (dark gray to black, compact, opaque, tough, no cleavage). These stones are used for drill bits, machine tools, glass cutters, dies for fine wires, engraving tools, and in phonographs. Black diamonds are preferred for drill bits. Their price is high: \$100 to \$150 per carat. Most of the black diamonds come from *Brazil*, and the remainder from numerous deposits in *Africa* and other countries.

Artificial Abrasives.—Artificial abrasives are extensively employed at present and are rapidly replacing the natural materials. The three important artificial abrasives are *carborundum*, *alundum*, and *steel shot* or *grains*.

Carborundum (silicon carbide, SiC) is made by fusing sawdust and quartz in an electric furnace. It has a hardness of about 9. *Alundum* and related aluminum oxide abrasives are produced by fusing bauxite in an electric furnace. The resulting products have the composition of corundum, Al_2O_3 , and a hardness of 9. These artificial materials, after being ground and sized, are molded into any desired form, mounted on paper or cloth, or sold as powders.

Uses of Abrasives.—The uses to which abrasives are put are so well known that little need be said about them. The demand for a rapid-cutting, durable abrasive that can be used at high speeds is very widespread. There are innumerable adaptations of abrasive cloth, wheels, and powders to special purposes. The pumicite of Kansas and Nebraska finds its greatest use in cleansers, scouring soaps, tooth pastes, and polishes. One packing company consumes thousands of tons annually in making "Old Dutch" cleanser. Diatomaceous earth is utilized in soaps, pastes, and polishing powders but to a much lesser extent than

pumicite. Other uses of abrasives have already been noted in the discussion.

Production of Abrasives. *Production of Natural Abrasives.*—Natural abrasives were produced in 28 states in 1928. The following table shows the amount and value of these abrasive materials:

TABLE 117.—AMOUNT AND VALUE OF THE NATURAL ABRASIVES PRODUCED AND IMPORTED IN THE UNITED STATES, 1927¹

Abrasive material	Amount, tons	Value	Value of imports
Millstones and buhrstones.....	.....	\$ 39,442	\$ 6,354
Grindstones.....	24,222	606,408	114,874
Pulpstones.....	9,016	902,429	
Oilstones and scythestones.....	956	228,245	45,303
Emery.....	1,341	16,787	272,533
Garnet.....	6,616	459,307	115
Diatomaceous earth.....	.....	900,000 ²	} 21,883
Tripoli (and rottenstone).....	30,299	514,986	
Pumice (and pumicite).....	57,430	278,516	159,430
Flint pebbles, etc.....	.....	.....	144,313
Grinding pebbles and tube-mill lining.....	6,288	89,321	
Totals.....	136,168	4,035,441	764,805

¹ Data from *U. S. Mineral Resources*, 1928, p. A9.

² Estimated on basis of former years.

Production of Artificial Abrasives.—The following table shows the production, by kinds, of the artificial abrasives in the United States in 1927:

TABLE 118.—ARTIFICIAL ABRASIVES PRODUCED IN THE UNITED STATES, 1927¹

Kind	Amount, tons	Value
Aluminum oxide.....	50,973	\$4,516,637
Silicon carbide.....	26,289	2,603,571
Metallic abrasives.....	13,364	839,683
Totals.....	90,626	\$7,959,891

¹ *U. S. Mineral Resources*, 1927, Part 2, p. 98.

Selected Readings on Abrasives

- EARDLEY-WILMOT, V. L.: *Abrasives, Mineral Industry*, pp. 1-10, 1925.
- GRISWOLD, L. S.: *Whetstones and Novaculites*, Geol. Survey Ark., vol. III, 1892. Old but good for general use.
- JACOBS, F. B.: "Abrasives and Abrasive Wheels," Henley Publishing Company, New York, 1919.
- LADOO, R. B.: "Non-Metallic Minerals," pp. 3-19, McGraw-Hill Book Company, Inc., New York, 1925. Very good account of abrasives. Special articles are: Corundum and Emery, pp. 162-175; Diamond, pp. 181-185; Diatomaceous

Earth, pp. 190-197; Garnet, pp. 241-256; Pumice and Pumicite, pp. 455-464; Tripoli, pp. 641-651.

RIES, H.: "Economic Geology," pp. 284-297, John Wiley & Sons, Inc., New York, 1925. Good. Contains bibliography.

Many of the chapters on abrasives in *U. S. Mineral Resources* and *Mineral Industry* contain interesting material.

BENTONITE

Composition of Bentonite.—Bentonite is a clay composed dominantly of a group of hydrous aluminum silicates. It contains from 5 to 10 per cent of the alkalis and alkaline earths and about 3 per cent ferric iron. Its composition differs in different localities and varies within the same bed.

Physical Properties of Bentonite.—Bentonite usually has a characteristic yellow or greenish-yellow color, but it may be white, gray, pink, or black. It has a waxy luster on a fresh surface and a variable fracture. Its most notable features are an extremely fine grain, marked plasticity, and an unusual absorbent ability. The grain is so fine that a high-power microscope usually fails to resolve the individual particles. A few specimens show rounded grains. The most distinctive feature of bentonite is its ability to absorb water; it takes up about seven times its own volume (even higher ratios are given). The material, after wetting, is very soft and feels like soap. When the powdered material is agitated in water, that of some varieties remains in suspension indefinitely, and even salt will not coagulate it. In other varieties, the suspended particles soon settle out.

Mode of Occurrence of Bentonite.—Bentonite occurs in beds that rarely exceed 5 or 6 feet in thickness. It is interbedded with shales many of which are dark-colored, whereas the bentonite is light-colored.

Origin of Bentonite.—Bentonite gets its name from its occurrence in the Benton group of the Cretaceous formation. Its occurrence in sedimentary rocks and its composition have led some geologists to believe that it is the alteration product of a bed of wind-blown volcanic ash. The alteration is supposed to have occurred soon after deposition. Other geologists do not accept a volcanic origin for the material.

Distribution of Bentonite in the United States.—Deposits of bentonite, or a bentonite-like material (for there is no agreement as to all the so-called "bentonite" deposits' actually being bentonite), are of widespread occurrence. Extensive deposits of high-grade bentonite (regarded as the type material) occur in numerous localities in *Wyoming*. The production comes largely from Rock River, Albany County; Medicine Bow, Carbon County; Cheyenne, Laramie County; and Newcastle, Weston County.

Important bentonite deposits are found between Barstow and Daggett, San Bernardino County, and near Otay, San Diego County, *Calif.*

forⁿia. *South Dakota* has important deposits in Ardmore, Fall River County, and Belle Fourche, Butte County. The Ardmore deposit is worked extensively.

Deposits of bentonite have been reported from *Montana, Idaho, Utah, Arizona, New Mexico, Texas, Tennessee, and Virginia.*

Uses of Bentonite.—The uses of bentonite are those based on its remarkable absorptive powers, and as a filler. As an absorbent, it is utilized in antiphlogistine and as a packing for horses hoofs. As a filler, it is employed in making paper and soap (it actually replaces some of the fatty base and alkali). It is used as an adulterant in drugs and candies. The fact that base exchange is easily brought about has led to the use of bentonite as a water softener. It removes the calcium of the hard water. It absorbs glycerin much better than does diatomaceous earth and hence is being tried out in the manufacture of dynamite. The possibilities of bentonite for filtering oil have not been fully developed, but the material is being studied along with a series of other possible filters.

Production of Bentonite.—The production of bentonite in the United States is not large, principally, it would seem, because the value of the material is not fully understood. The development of more uses will, of course, stimulate production.

Selected Readings on Bentonite

DAVIS and VACHER: *Bentonite, Its Properties, Mining, Preparation, and Utilization*, U. S. Bur. Mines *Tech. Paper* 438, 1928.

LADOO, R. B.: "Non-Metallic Minerals," pp. 91-96, McGraw-Hill Book Company, Inc., New York., 1925.

ROSS and SHANNON: *The Minerals of the Bentonite and Related Clays and Their Physical Properties*, *Jour. Am. Cer. Soc.*, vol. IX, pp. 79-95, 1926.

SPENCE, H. S.: *Bentonite*, Canada Dept. Mines *Rept.* 626, 1924.

DIASPORE

Diaspore is a recent addition to the list of earth materials having important industrial uses. It was discovered in 1917 in the flint fire-clay deposits of the north-central Ozark region of Missouri, and production began the next year. These are the only deposits of diaspore clay known anywhere, and the descriptions given here are of them. Diaspore had long been known (it was named by Haüy over 100 years ago) but only as a constituent of metamorphic rocks.

Composition of Diaspore and Diaspore Clays.—Diaspore is a hydrous aluminum oxide. It contains 85 per cent Al_2O_3 and 15 per cent H_2O . The alumina (Al_2O_3) content of a valuable diaspore clay must exceed 70 per cent. The name "burley clay" is given to the material carrying less than that. It is too poor to market, but attempts are being made to find a use for it. The diaspore of the clay contains less than 1 per cent of ferric oxide but is remarkably high in titanium oxide, some of the material

running over 3 per cent. The following analyses, furnished by the Missouri Bureau of Geology and Mines, shows the range in composition of these diaspore clays:

TABLE 119.—ANALYSES OF DIASPORE CLAYS FROM THE NORTH-CENTRAL OZARK REGION OF MISSOURI¹

Material	1	2	3	4
Silica, SiO ₂	15.60	11.58	3.89	7.44
Alumina, Al ₂ O ₃	64.46	68.50	76.21	73.58
Ferric oxide, Fe ₂ O ₃	0.42	0.88	0.98	0.93
Titania, TiO ₂	2.60	3.40	3.52	3.99
Lime, CaO.....	0.92	0.26	0.08	"
Magnesia, MgO.....	1.52	0.13	0.06	"
Soda, Na ₂ O.....	0.37	1.34	0.79	"
Potash, K ₂ O.....	0.81	0.46	0.24	"
Ignition loss.....	13.52	13.91	14.20	14.12
Total.....	100.22	100.46	99.97	100.06

1 Burley clay, Franklin County.

2 Burley clay, Gasconade County.

3 Diaspore clay, Maries County.

4 Diaspore clay, Maries County.

" Not determined.

¹ Analyst, H. W. Mundt, Mo. Bur. Geol. and Mines.

Physical Properties of Diaspore and Diaspore Clay.—The diaspore of metamorphic rocks is well crystallized; usually as thin, flattened prismatic forms; but also as foliated and massive forms. It has a hardness of 6.5 to 7 and a specific gravity of 3.3 to 3.5. It is brittle and is white, gray, yellow, or brown.

The diaspore of the flint fire-clay deposits always consists of oolites or irregularly rounded grains, which rarely exceed $\frac{1}{4}$ inch in diameter and are usually less than $\frac{1}{8}$ inch. The grains are usually massive, only a few showing a radial structure. The diaspore is hard and fairly tough and is generally white to light gray. The enclosing clay is white, gray, or buff or more deeply colored by iron oxides. The diaspore clay ranges in texture from a dense, hard flint clay (which contains only a few grains of diaspore) to a harsh, rough, porous rock (rich in diaspore).

Mode of Occurrence of the Diaspore Clays.—The diaspore clays always occur in sink-hole deposits in association with high-grade flint fire clays. The deposits are typically basin shaped (Fig. 243) and are usually circular or elliptical in plan. They range in size from small "pot-

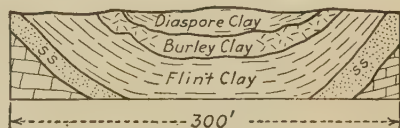


FIG. 243.—Ideal section of a diaspore clay pit in central Missouri. Note sandstone along the sides of the pit (many of which are sinkholes in dolomite), with sandy flint clay above and burley clay next to the diaspore clay. Diaspore clay carries 70 per cent or more of Al₂O₃, and burley clay from 50 to 70 per cent.

holes" to areas 800 feet across. The majority of them are shallow basins, few attaining a depth of 100 feet.

Distribution of Diaspore Deposits.—The deposits of diaspore clay occur in the central part of Missouri, in Osage, Gasconade, Franklin, Maries, Phelps, and Crawford counties. They are always found associated with the Pennsylvanian formations of the area. The flint fire clay with which the diaspore occurs had been worked for years, and the diaspore clay had been thrown aside or left standing in the pit, as it had been found to be injurious in burning the other clay. That the discarded clay was high in alumina had been known for several years, but the identity of the mineral or the possible use of the clay in high-alumina refractories was not discovered until 1917. Most of these deposits are favorably located for shipping, and, as a result, production (which began in 1918) has climbed rapidly.

Uses of Diaspore.—Although the high-alumina content of diaspore (it is higher than that of bauxite, which contains 74 per cent Al_2O_3) would suggest its use for obtaining metallic aluminum, very little of the material has been so used. The chief use of the clay has been as alumina refractories which are of a higher grade than bauxite refractories. It is also employed in the manufacture of abrasives.

Production of Diaspore.—The figures for the production of diaspore were not separated from those of the flint fire clay until 1922. The following table gives the production by years since that date:

TABLE 120.—PRODUCTION AND VALUE OF DIASPORE, 1922–1927¹

Year	Amount, tons	Value
1922	13,384	\$109,229
1923	10,617	54,450
1924	9,252	47,407
1925	15,177	102,064
1926	18,483	100,823
1927	40,085	229,093

¹ Data from Mo. Bur. Geol. and Mines.

Selected Readings on Diaspore

- LADOO, R. B.: "Non-Metallic Minerals," pp. 186–189, McGraw-Hill Book Company, Inc., New York, 1925.
 McQUEEN, H. S.: *Min. and Metallurgy*, pp. 271–275, 1928.
 —: *Jour. Am. Ceramic Soc.*, 1929.
 WHERRY, E. T.: Diaspore, *Am. Mineralogist*, vol. II, p. 144, 1917; vol. III, p. 154, 1918.

DIATOMACEOUS EARTH

Diatomaceous earth has long been utilized for numerous purposes, and no less than 15 different names have been applied to it. Inasmuch

as the material consists of the remains of diatoms, the name "diatomaceous earth" would seem to be sufficiently accurate and correct, and it will be the only one used here. Certainly, the material should never be called "tripoli" (as sometimes happens), which is an entirely different substance.

Composition of Diatomaceous Earth.—Diatomaceous earth is an accumulation of the siliceous remains of diatoms and, more rarely, other siliceous organisms. Diatoms are small plants living abundantly in certain parts of the ocean. They make use of the silica in the sea water in building their hard parts. The silica of diatomaceous earth is really a form of opal, as it contains from 3 to 10 per cent water (the water content of opal ranges from 2 to 13 per cent). A good grade of diatomaceous earth contains over 80 per cent silica, from 3 to 9 per cent aluminum and ferric oxides, and from 1.5 to 3.5 per cent alkalis. The percentage of aluminum oxide is greater where the material is clayey, and some deposits contain considerable calcium carbonate.

Physical Properties of Diatomaceous Earth.—The diatom remains that compose the diatomaceous earth are minute cells very few of which can be seen with the naked eye (Fig. 153, p. 395). The earth is very porous and light; when dry, it will float on water. It has a rough feel that distinguishes it from kaolin and clays. Its color is usually pure white, but it may be tan, buff, pink, red, or gray. As the material has great absorptive power, it may contain from 25 to 45 per cent of mechanically included water. This water is largely lost on drying in the sun and is entirely lost at 100°C. The specific gravity of the earth is 2.1 to 2.2; but, because of the minute size of the cells and the great porosity of the material, the specific gravity of the dry material in blocks is 0.45 and of the dry powder, even less. The significant physical properties of diatomaceous earth are its porosity, absorptive power, light weight (compared to other sediments), low thermal conductivity, and large surface area in comparison to the average diameter of the particles. It is insoluble in acids (save hydrofluoric) and neutral solutions but is soluble in alkaline solutions.

Mode of Occurrence of Diatomaceous Earth.—Diatomaceous earth occurs in beds which range from a few inches thick to the extraordinary thickness of 2,000 feet or more (some California beds are stated to be over 4,000 feet thick, but these are really diatomaceous shales). The material of workable beds must have a high degree of purity, and such beds (save in California) are less than 100 feet thick. The deposits of California (probably the largest known) greatly exceed this thickness. Diatomaceous earth is interbedded with shales, sandstones, and even limestones.

Distribution of Diatomaceous Earth in the United States.—Excellent deposits of diatomaceous earth are world wide in their distribution.

They are scattered all over the United States. The best deposits are in *California*, especially in Santa Barbara, Monterey, Orange, San Luis Obispo, and Shasta counties. The most extensively worked deposits are in Santa Barbara County near Lompoc. These beds are thick and cover several square miles. They contain very pure diatomaceous earth, which grades from loose to hard, compact material some parts of which have been cemented into a hard, flintlike rock. The earth can be sawed or cut into bricks, slabs, blocks, and other forms.

Oregon has several large deposits of diatomaceous earth two of which are being actively worked. One of these is near Terrebonne, Deschutes County, and the other near Harper, Malheur County. There are several areas of diatomaceous earth in *Washington*, but those in Kittitas, Grant, and Skagit counties are the leading producers. *Nevada*, *Utah*, and *New Mexico* have deposits of the earth, and several are known in *Nebraska*, though none of them are worked.

In the eastern part of the United States, deposits of diatomaceous earth occur in *Florida*, *Virginia*, *Maryland*, *New Jersey*, *New York*, *Massachusetts*, *New Hampshire*, and *Maine*, but only those of New York and New Hampshire have been productive in recent years.

Uses and Production of Diatomaceous Earth.—Although the production of diatomaceous earth is listed with Abrasives in the *Mineral Resources* of the U. S. Bureau of Mines, its use as an abrasive is a minor one. The greatest value of the material lies in its insulating properties. The earth consists of an immense number of minute cells each of which is filled with air. This immovable air acts as an ideal insulator. It is also a factor in causing the lightness of the material.

The powder or bricks of the diatomaceous earth may be used directly or may be treated for special purposes. In the form of sawed bricks, artificial bricks, and powder, diatomaceous earth is used for heat and sound insulation. As the material is a fair-grade refractory, it is used where lightness in a fireproofing material would be of value. It is an excellent absorbent and is employed for that purpose in making dynamite and other materials. It has excellent filtering qualities, permitting the passage of liquids that do not readily pass through other filtering media. Its use as an abrasive has already been discussed (p. 597).

Diatomaceous earth is used in making rubber, phonograph records, plaster, and magnesite flooring. It is used in ceramics (furnishing silica for body and glazes); as a structural material (of light weight but of low strength); as a bleaching agent (not so efficient as fullers' earth); and in various chemical uses (as a catalyzer, for example).

For the production of diatomaceous earth in the United States, see Table 117 under Abrasives.

Selected Readings on Diatomaceous Earth

- ARNOLD and ANDERSON: Diatomaceous Earth Deposits of Northern Santa Barbara County, California, U. S. Geol. Survey *Bull.* 315, pp. 438-447, 1907.
- HASTINGS, E. S.: Diatomaceous Earth, *Rock Products*, vol. XXXII, pp. 50-54, 1929. Contains illustrations of diatoms.
- LADOO, R. B.: "Non-Metallic Minerals," pp. 190-197, McGraw-Hill Book Company, Inc., New York, 1925. Contains bibliography.
- RIES, H.: "Economic Geology," pp. 318-321, John Wiley & Sons, Inc., New York, 1925.
- See, also, *U. S. Mineral Resources and Mineral Industry*.

FELDSPAR

The feldspars are the most abundant minerals in the outer part of the earth's body. They constitute, there, approximately 60 per cent of all igneous rocks and a slightly smaller percentage of all rocks. They are not of economic importance, however, unless they occur in considerable quantities in accessible deposits.

The Feldspar Minerals and Their Composition.—The feldspars include several different minerals, which, for the purposes of this book, may be divided into two groups: the *potash (and soda) group* and the *soda-lime group*. The minerals included in each are as follows:

Potash (and soda) group		Soda-lime group	
Orthoclase.....	KAlSi_3O_8	Albite.....	$\text{NaAlSi}_3\text{O}_8$
Microcline.....	KAlSi_3O_8	Oligoclase.....	} mixtures of albite and anorthite
Anorthoclase.....	$(\text{NaK})\text{AlSi}_3\text{O}_8$	Andesine.....	
		Labradorite.....	
		Bytownite.....	
		Anorthite.....	$\text{CaAl}_2\text{Si}_2\text{O}_8$

So far as their use is concerned, it makes no difference whether the feldspar is dominantly a potash or a soda variety, but lime-rich varieties are not so satisfactory for ceramic purposes. The composition of the feldspars is essentially that indicated by their formulas. Pink and red feldspars (more characteristic of the potash varieties) contain small amounts of ferric oxide, which do not, as a rule, prove detrimental to the use of the feldspar in ceramics. Associated iron-rich minerals are injurious.

Physical Properties of Feldspar.—Most feldspar is white or light shades of pink, red, yellow, or gray. Dark varieties occur only rarely, especially in workable deposits. Feldspars have a hardness of 6, a specific gravity of 2.54 (orthoclase) to 2.76 (anorthite), and two good cleavages. They do not melt at a definite temperature; but, with an increase in temperature, they soften gradually. This temperature is different for the different members of the group. For the potash members, it is about $1,310^\circ\text{C}$.; for the pure soda members, it is above $1,250$ but below $1,310^\circ\text{C}$.; and for the lime members, it is about $1,530^\circ\text{C}$. On cooling,

the varieties rich in potash and soda become solid glass without crystallizing. On the other hand, lime-rich varieties become partially or wholly crystalline on cooling.

Mode of Occurrence of Commercial Feldspar.—Economic deposits of feldspar occur as very coarse-grained veins or dike-like masses in association with granites and other grained igneous rocks. These occurrences are known as *pegmatite dikes*. The only mineral in the dike may be feldspar, though this is rarely the case. Quartz, muscovite, biotite, and a group of minerals that are sometimes of more value than the feldspar (such as tourmaline, beryl, garnet, and about 50 rare minerals) are usually present.

The feldspar occurs in crystals of all sizes, of which the maximum is 20 feet in diameter. Large size is a notable feature of all the minerals in a pegmatite and, of course, makes possible their economic use. In most of the deposits worked, the average size of the feldspar crystals is from 4 to 5 feet across. The dikes may be from a few to hundreds of feet across and a mile in length and are, for the most part, lens shaped (Fig. 244).

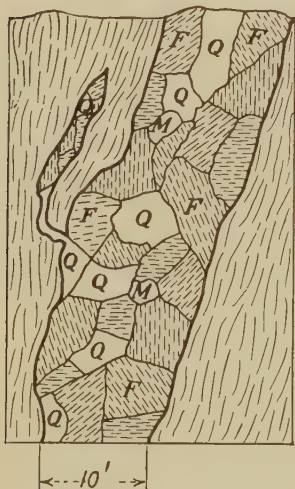


FIG. 244.—Pegmatite dike showing the large size of the crystals and their irregular distribution. F, feldspar. Q, quartz. M, mica.

Origin of Pegmatite Dikes.—Pegmatite dikes were formed during the solidification of an igneous mass. The feldspars, quartz, micas, and other minerals were concentrated in a solution containing an abundance of water and probably several gases. This solution was forced into the surrounding rock, where, because of the large amounts of water and gases present, the deposition of the minerals was slow. This slow deposition permitted the growth of large crystals. It is generally believed that the crystallization in the dikes occurred below 575°C.

Distribution of Feldspar Deposits in the United States.—Commercial deposits of feldspar are found in *Maine, New Hampshire, Massachusetts, New York, Connecticut, Pennsylvania, Maryland, Virginia, North Carolina, Georgia, Texas, Wisconsin, South Dakota, Colorado, Arizona, New Mexico, and California*. (The italics indicate the states producing the material in 1928.) The crystalline belt extending from Maine to North Carolina is the chief feldspar area of the United States. It produced 90 per cent of the total mined in 1928.

Uses of Feldspar.—The principal use of feldspar is in the ceramic industry, where it is used largely as a flux. It fuses at a lower temperature than the clay or quartz and becomes a binder without excessively high temperatures in the kiln. It is used in the body of the ware

(comprising 10 to 35 per cent of the materials), in the glaze (comprising 30 to 50 per cent), and in glass. The potash-soda-rich varieties are employed in glazes because they do not crystallize but form a clear glass when cool. Feldspar is an important constituent of enamels for tile, porcelains, and the innumerable number of enameled wares for kitchen, laundry, and sanitary purposes.

Other uses are as an abrasive in scouring-soap and polishes (it is softer than glass; hence, does not scratch it); as a binder in abrasive wheels; and (in coarse particles) as a poultry grit; in roofing materials; and as a dash material for stucco or plaster. Very pure feldspar is used in making artificial teeth.

Production of Feldspar in the United States.—The production of crude feldspar in the United States has shown a steady increase during recent years, a growth thought to be due to the formation of larger companies which own their own mines and mills and produce, as a result, more uniform grades of ground feldspar. North Carolina produced 50 per cent of the total output of feldspar in 1928; New Hampshire was second, producing 14 per cent; and Maine third, producing 12 per cent. The value of the material ranged from about \$6 per ton for North Carolina feldspar to \$8 per ton for the Maine product. Production in 1928 amounted to 210,811 long tons, valued at \$1,418,975, or an average price of \$6.73 per ton.¹

Selected Readings on Feldspar

- BASTIN, E. S.: The Feldspar Deposits of the United States, U. S. Geol. Survey *Bull.* 420, 1910.
- : The Geology of the Pegmatites and Associated Rocks of Maine, U. S. Geol. Survey *Bull.* 445, 1911. Very good discussion of feldspars and other minerals in pegmatites.
- LADOO, R. B.: "Non-Metallic Minerals," pp. 212–222, McGraw-Hill Book Company, Inc., New York, 1925.
- RIES, H.: "Economic Geology," pp. 321–327, John Wiley & Sons, Inc., New York, 1925.
- WATTS, A. S.: Feldspars of New England and Northern Appalachian States, U. S. Bur. Mines *Bull.* 92, 1916.
- : Mining and Treatment of Feldspar and Kaolin in the Southern Appalachian Region, U. S. Bur. Mines *Bull.* 53, 1913.

FULLERS' EARTH

Fullers' earth is a clay that possesses very marked absorbent powers, especially of coloring materials in oils, fats, and greases. The name is derived from its former use by fullers. It was used as a filler of cloth and at the same time to absorb any oil or fats on the thread.

Previous to 1895, all fullers' earth used in the United States was imported, but in 1893 a large deposit was accidentally discovered at Quincy,

¹ U. S. Bur. Mines.

Florida. Unsuccessful attempts were made at first to use this clay in brick-making, but an Alsatian workman noticed its resemblance to German fullers' earth, and at his suggestion, tests were made which determined its real value.

Characteristics of Fullers' Earth.—The chemical composition of fuller's earth has repeatedly been shown to be of no value in determining its absorbent power. This power is, apparently, entirely dependent upon the physical character of the materials in the clay, of which colloids are the most important. The bleaching power of fullers' earth is very different for different earths and is different for different oils. Some of the earths are plastic; others are non-plastic. Most of them fall to pieces rapidly in water. Nearly all show an acid reaction, it is said, yet no acid is present. Some of the earths can be treated by heat and used again

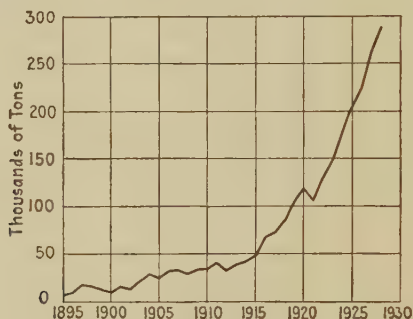


FIG. 245.—Production of fuller's earth in the United States from 1895 to 1928. (Data from U. S. Bur. Mines.)

and again, and others cannot. The value of a clay can be determined only by actual tests on the particular materials to be bleached.

Distribution of Fullers' Earth in the United States.—Fullers' earth has been reported from 21 states, but at present production is confined to 8. They are *Arizona, Colorado, Florida, Georgia, Illinois, Massachusetts, Nevada, and Texas*. Most of the production comes from Georgia (first) and Florida (second).

Uses of Fullers' Earth.—The chief use of fullers' earth is in bleaching all kinds of oils, greases, and fats. Some fullers' earth is best adapted for bleaching vegetable oils, others for mineral oils. For bleaching mineral oils, the clay is dried and ground to various sizes dependent upon the viscosity of the liquid to be bleached. The oil is allowed to percolate through it. The first oil coming through is colorless but as the clay becomes saturated with coloring matter, the filtered oil will be colored. After bleaching mineral oils, the clay is rejuvenated by heating (but not to the point of dehydration) and is ready for use again. In bleaching vegetable oils, clay, to the extent of 1 to 10 per cent of the weight of the

oil to be bleached, is mixed with the oil. It is heated to nearly 100°C., stirred briskly, and then filtered. The earth is not used again after bleaching vegetable oils.

Fullers' earth has a few minor uses, such as in printing, in detecting coloring agents in food products, and as a binder for abrasives.

Production of Fullers' Earth in the United States.—There has been a steady growth in the production of fuller's earth in the United States during recent years (undoubtedly due to its use in refining petroleum) and a steady decline in imports, as the American product is very satisfactory for all purposes. The production of fullers' earth from 1895 to 1928 is shown in Fig. 245. The amount produced in 1928 was 287,012 tons, valued at \$3,895, 991.¹

Selected Readings on Fullers' Earth

PARSONS, C. L.: Fullers' Earth, U. S. Bur. Mines *Bull.* 71, 1913.

PORTER, J. T.: Properties and Tests of Fullers' Earths, U. S. Geol. Survey *Bull.* 315, pp. 268-290, 1906.

LADOO, R. B.: "Non-Metallic Minerals," pp. 231-240, McGraw-Hill Book Company, Inc., New York, 1925. Contains bibliography.

RIES, H.: "Economic Geology," pp. 337-340, John Wiley & Sons, Inc., New York, 1925. Contains bibliography.

See U. S. *Mineral Resources and Mineral Industry*.

GEMS AND SEMIPRECIOUS STONES

Gems are minerals that, because of their brilliancy, color, hardness, and rarity, are valued for use as personal adornment. The term "gem" should be applied to the stone after cutting and polishing; the uncut mineral should be called a "gem stone." The name *gem* is applied particularly to a group of minerals that includes the *diamond*, *ruby*, *sapphire*, and *emerald*. There are several other stones of less value, such as the *topaz*, *spinel*, *garnet*, *turquoise*, *chrysoberyl*, *opal*, *zircon*, and *tourmaline*, that are sometimes called *semiprecious stones*.

Characteristics of Gems.—The gem stones usually show a somewhat crystalline form, but they may be massive or any shape. The cutting destroys the original shape. The brilliance of gems (highest in the diamond) is due to the reflection and refraction of the light from within the stone. The color of a gem may be inherent in the mineral, but it is usually due to small amounts of foreign material. A gem must be hard enough to retain its polish, for a stone is subjected to considerable wear when worn daily. Rarity is, of course, essential in giving value to a gem; and it may be rarity of quantity, size, or color. The following table gives the names, composition, hardness, chief color or colors, and the chief sources of the most important gems and semiprecious stones:

¹ U. S. Bur. Mines.

TABLE 121.—COMPOSITION, HARDNESS, COLOR, AND CHIEF SOURCES OF THE MOST IMPORTANT GEMS AND SEMIPRECIOUS STONES

Name	Composition	Hardness	Chief color or colors	Chief sources, in order of importance
Diamond.....	Pure carbon	10	Colorless, blue-white, yellow, straw	Union of South Africa, Congo, Gold Coast, British Guiana, Brazil
Ruby.....	Al_2O_3	9	Red	Burma, Ceylon
Sapphire.....	Al_2O_3	9	Blue	Ceylon, Burma, Queensland, Montana
Emerald.....	$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$	7.5 to 8	Green	Colombia
Topaz.....	$(\text{AlF})_2\text{SiO}_4$	8	Straw-yellow	Brazil, Russia
Garnet.....	Complex	6.5 to 7.5	Red, green	Arizona, Bohemia, Ural Mountains
Zircon.....	ZrSiO_4	7.5	Red, orange	Ceylon, Siam
Opal.....	$\text{SiO}_2 \cdot \text{H}_2\text{O}$	5.5 to 6.5	Play of colors	New South Wales, Hungary, Nevada, Mexico
Amethyst.....	SiO_2	7	Purple	India, Ceylon, Persia, Brazil
Tourmaline.....	Complex	7 to 7.5	Green, pink	California, Urals, Madagascar
Spinel.....	$\text{MgO} \cdot \text{Al}_2\text{O}_3$	8	Red	Ceylon, Burma, Siam
Peridot.....	$(\text{MgFe})_2\text{SiO}_4$	6.5 to 7	Green	Arizona
Turquoise.....	Complex	5 to 6	Sky-blue, bluish green	New Mexico, Persia, Turkestan
Kunzite.....	Complex	6.5 to 7	Lilac	California, Burma, China
Jade.....	Complex	6.5 to 7	Apple-green, other shades	Siberia, Chile, California
Lapis lazuli....	Complex	5 to 5.5	Deep blue	

Mode of Occurrence of Gem Stones.—Gem stones, because of their hardness and insolubility, are usually found in sands and gravels along streams and in the soils over the parent rock. They also occur in the original rock, but the major part of all gem stones found, aside from the diamond and opal, comes from alluvial deposits. Gem stones occur in veins, dikes, and necks or plugs; in pegmatites; metamorphic rocks; and as replacements in metamorphosed limestones and other rocks.

Origin of Gem Stones.—A complete discussion of gem stones is impossible here. Some of them, such as the diamond, zircon, garnet, sapphire, and peridot, are original constituents of igneous rocks, having been formed by crystallization during the solidification of the rock itself.

Diamonds occur in a peridotitic rock, called "blue ground." The source of the carbon entering the diamond has caused considerable

speculation. Some scientists have suggested that they crystallized from carbon that resulted from the melting of carbonaceous shales; others think that the diamond was an original constituent of the rock. As diamonds occur in peridotites in different parts of the world, there seems to be little doubt but that they are of igneous origin in those occurrences. Those found in alluvial deposits or sandstones and quartzites were derived from unknown rocks.

Sapphires crystallize out of a magma high in alumina. The excess of alumina may have come from the melting of an alumina-rich rock, such as a shale, or it may have been present originally. *Rubies* may form in the same way, but the best deposits (those in Burma) are found in a metamorphosed limestone, which contained the alumina in some aluminous mineral. Sapphires are also found in this deposit.

Zircon, *garnet*, and *peridot* all occur in igneous rocks: the last two in basic rocks; zircon generally in acidic rocks but also in others. Garnet also occurs in metamorphic rocks.

Emeralds are found in pegmatite veins and alluvial gravels. *Topaz* is found in igneous rocks of various types but is especially associated with granitic rocks. *Amethyst* and the other forms of quartz are commonly found in veins under a wide range of conditions. *Tourmaline* occurs in igneous and metamorphic rocks, but the best gem stones come from pegmatite veins. *Spinel* is a mineral of metamorphic rocks.

Opals are deposited by hot waters near the surface. Their colors are due to the breaking up of the light rays on the interior, probably by tiny shrinkage cracks. Opals are amorphous and occur as replacements of wood, fossil bones, teeth, and shells; but the best gem material occurs in irregular veins in sedimentary rocks and, to a lesser extent, in acid lava flows. Black opals having a lovely play of colors are found in the Australian mines. Opals must receive more care than most stones, as they are liable to chip if exposed to rapid changes in temperature.

Turquoise is a mineral formed by hot solutions' attacking and altering certain rocks. Its blue color is due to the presence of a small amount of copper. Most turquoise is amorphous and is apt to change color with the loss of some of its water (due to exposure after being mounted), a change that, contrary to superstition, has nothing to do with the wearer.

Gems as Amulets.—It seems incredible that in the twentieth century so many people should still believe in the value of gems as amulets or charms. The lore regarding these beliefs is interesting, just because it shows how easily man is influenced by foolish superstitions. Every gem has certain supposed qualities that protect the wearer from various ills. The fading of the turquoise and opal, due to their natural loss of water, is still regarded by many as an evil omen. Even the dulling of the luster of a gem as the result of wear spells disaster to some foolish individuals.

Distribution of Gem Stones in the United States.—The United States contains no valuable deposits of gem stones. *Sapphires* (about \$22,000 worth in 1926) are mined at Yogo Gulch, Fergus County, *Montana*. *Diamonds* (occurring in a disintegrated peridotite rock) have been produced for a number of years near Murfreesboro, Pike County, *Arkansas*. Several thousand stones, mostly small, have been found there. *Garnets* occur in small quantities in *Arizona*. Large deposits of *opal* are found about 50 miles north of Winnemucca, *Nevada*. This material requires processing before cutting, and little has yet been done with it. Excellent pink and green gem *tourmaline* comes from Pala, San Diego County, *California*. The same deposit produces *kunzite*. Excellent *turquoise* is found in the Burro Mountains, Grant County, *New Mexico*. These deposits have been worked a long time. Very fine gem stones of peridot occur near Fort Defiance, *Arizona*. Rarely, other gems are found, but no commercial deposits of them are known.

Importation of Gems into the United States.—The absence of important deposits of gem stones in the United States makes it the largest importer of gems in the world. According to Kunz,¹ over \$80,000,000 worth of gems (including pearls) and imitations was imported in 1926. The average importation per year for the three preceding years was \$75,000,000.

The African Diamond Deposits.—The world's supply of diamonds comes from the mines of Africa. Before the World War, 96 per cent of all diamonds came from *South Africa*, but this percentage is now about 50, on account of alluvial deposits and mines discovered in other parts of the continent. The production at present is from the *Union of South Africa*, *Congo*, *Angola*, the *Gold Coast*, *Southwest Africa*, and *Tanganyika*. The major production comes from the Union of South Africa; Congo is second. The Union of South Africa had produced 81.7 per cent of the world's output of diamonds in 1926.

The diamonds in the Union of South Africa are in alluvial gravel and in pipes of igneous rock (kimberlite or blue ground). These pipes are nearly vertical, and some have been mined as open cuts to depths of 1,000 feet. Others are worked as underground mines. A load of the blue ground (1,600 pounds) averages about $\frac{1}{4}$ carat of diamonds. They are recovered by washing the rock material and passing it over tables covered with grease. The diamonds adhere to the grease and the waste rock goes on.

Production and Price of Diamonds.—Far more diamonds are produced than are sold. The Diamond Syndicate has a control so complete that it puts on the market a limited quantity and names the price. The value per carat of the cut diamonds imported into the United States in 1926 was listed as \$92.50, yet the public paid about \$500 for a one-

¹ KUNZ, G. F., *Mineral Industry*, 1926, p. 564.

carat stone of the first water. Before the World War, the annual production of diamonds was about 5,000,000 metric carats (1 metric carat = 200 milligrams). From 1920 to 1925, the average yearly production was 2,943,000 metric carats.

Some years ago, Ball¹ estimated that to the end of 1919, there had been produced, from the world's diamond mines, 187,900,000 metric carats of diamonds. By the end of 1925, 205,558,855 metric carats had been produced.² In avoirdupois weight, the amount of all the diamonds that have been produced is 45.22 short tons. All these diamonds piled together would form a cube only 7.43 feet square, and their value would be billions of dollars.

Comparative Value of Gems.—Questions are often asked concerning the comparative value of the precious stones. The following table of values of very fine stones is of interest in this connection:

TABLE 122.—COMPARATIVE VALUE OF THE PRECIOUS STONES AND PEARLS¹

Gem	Value		
	Per carat	Per gram	Per avoirdupois ounce
Sapphire.....	\$ 500	\$ 2,500	\$ 70,875
Diamond.....	700	3,500	99,225
Ruby.....	1,000	5,000	141,750
Emerald.....	1,000	5,000	141,750
Pearl, 10-grain ²	2,000	10,000	283,000

¹ KUNZ, G. F., *Mineral Industry*, 1924, p. 602.² Based on \$20 per grain.

Selected Readings on Gems

KRAUS and HOLDEN: "Gems and Precious Stones," McGraw-Hill Book Company, Inc., New York, 1927. Excellent book on gems.

KUNZ, G. F.: "Gems and Precious Stones of North America," New York, 1892.

—: Precious Stones, *Mineral Industry*, 1926, pp. 563–591. See reports for other years, also.

SMITH, G. F. H.: "Gem-Stones," Methuen and Co., London, 1923.

WILLIAM, G. F.: "The Diamond Mines of South Africa," The Macmillan Company, New York, 1902.

GRAPHITE

Composition and Physical Properties of Graphite.—Graphite, like the diamond, is a pure-carbon mineral, but it crystallizes in thin, opaque, black flakes. In one variety, these flakes are so small that the graphite is called "amorphous." Graphite has a soft, greasy feel. It will mark paper; hence, the name "graphite," which means "to write,"

¹ BALL, S. H., *Diamonds*, *Eng. and Min. Jour. Press*, vol. CIX, pp. 1202–1208, 1920.

² *Mineral Industry*, 1926, p. 568.

and its extensive use in "lead" pencils that contain no lead. Graphite is insoluble in acids and is infusible. If oxygen is present, it will burn at 650 to 700°C., but it will not melt below 3,000°C. (5,432°F.).

Mode of Occurrence of Graphite.—Graphite occurs as *crystalline flakes* and *fibrous forms* in dikes and veins and as *small flakes* in schists, marbles, gneisses, quartzites, and metamorphosed coal beds. It is also found in igneous rocks. Graphite having no evident crystalline form is called "amorphous" material. It is put on the market as "flake" and "amorphous."

Origin of Graphite. *Igneous Origin.*—The occurrence of graphite in pegmatite dikes (Fig. 246), granites, and syenites indicates that such deposits are of magmatic origin. Graphite occurring in meteorites and in the iron-bearing basalts of Ovifak, Greenland, is probably of similar origin. The graphite vein deposits of Ceylon and Montana appear to have been deposited from carbon-rich vapors arising from deeper zones.

Organic Origin.—The graphite of schists, gneisses, quartzites, and marbles may have originally been organic carbonaceous matter, which, during the metamorphism of the enclosing rocks, was converted into graphite. The sedimentary origin of many of these deposits is very evident. Coal beds have been altered to graphite by the heat from igneous rocks adjacent to them, and, in these instances, there can be no doubt as to the material's organic origin.

Distribution of Graphite.—Graphite-bearing beds are widely distributed throughout the world.

Graphite in the United States.—In spite of the numerous graphite deposits in the United States, the production is from a relatively few localities. The accompanying map (Fig. 247) shows the locations of the most important deposits. In 1928, *Alabama, Georgia, Michigan, Nevada, Rhode Island, and Texas* were the only states' reporting a production of graphite.

A high-grade, coarsely crystalline graphite occurs in veins (some are 16 inches across) at Dillon, Beaverhead County, Montana. The deposits in the eastern part of the United States are associated with schists, quartzites, marbles, pegmatites, and other igneous rocks. The deposits worked are in the schists. Both flake and amorphous graphite are produced. Many of the deposits are deeply weathered, the graphite being obtained from mantle rock. Most of the ore contains from 2.5 to 7 per cent graphite. The notable exception is the deposit in Rhode Island, where the content reaches 50 per cent. The Texas deposit runs from 6 to 10 per cent graphite.

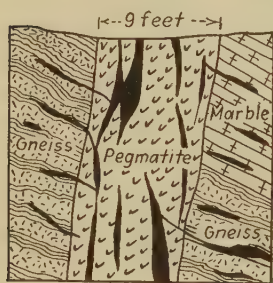


FIG. 246.—Sketch showing the occurrence of graphite (black areas) in pegmatite, gneiss, and marble in Buckingham Township, Quebec. (Modified after Osann, Lindgren, "Mineral Deposits," p. 825.)

Foreign Graphite Deposits.—For a long time, high-grade, coarsely crystalline graphite has been mined in *Ceylon*. It comes from veins, some of which are several feet in width. The other leading foreign deposits are in *Chosen* (amorphous graphite); *Austria* (amorphous and flake graphite); *Madagascar* (flake graphite); *Germany* (crystalline graphite); *Mexico* (amorphous graphite); *Czechoslovakia* (amorphous and flake graphite); *Italy* (amorphous graphite); and *Canada*.



FIG. 247.—Location of the graphite deposits of the United States.

Uses of Graphite.—The change in the uses of graphite illustrates how innovations in industrial practices lead to radical changes in the use of a product. The following table illustrates this:

TABLE 123.—CHANGES IN THE USES OF GRAPHITE ¹

Use in	Percentages			
	1913	1918	1923	1924
Crucibles.....	55	45	15	13
Foundry facings.....	10	25	44	52
Pigments and paints.....	5	5	16	18
Lead pencils.....	5		9	5
Stove polish.....	15	5-10		
Commutator brushes.....	2	....	9	5
Lubricants.....	5	10		
Other uses.....	3	10-5	7	7
Total.....	100	100	100	100

¹ Data from several sources.

The figures for the first two uses (crucibles and foundry facings) represent nearly complete reversals in the years 1913 and 1924. This change was due to the shift from the use of graphite crucibles for melting brass, bronze, steel, aluminum, babbitt metal, and solder to electrical-furnace methods of smelting these materials.

The manufacture of crucibles required large amounts of flake graphite, a purpose for which amorphous graphite is unsuited. Amorphous graphite is very satisfactory for foundry facings, pigments and paints, stove polish, and lead pencils.

Graphite, either alone or in oils and greases, is an excellent lubricant. It is used alone in textile-weaving machines where oils would be injurious to the fabrics. Graphite paints and stove polishes are used extensively on metal surfaces. Graphite in pencils is a minor but important use. That for pencils is mixed with clay and other materials; the amounts vary with the hardness of the pencil desired (the more clay the harder the pencil). A common mixture for this purpose is graphite, 30 parts; clay, 9 parts; stibnite, Sb_2S_3 , 9 parts; tallow, 1 part. Some idea of the extent of the pencil and pencil-lead industry in the United States is shown by the fact that 10,016,581 dozen pencils, valued at \$2,144,614, were exported in 1926.

Other uses of graphite are as electrodes, fillers for dry batteries, glaze and polish for powder and shot, fertilizer filler, and in pipe cement.

Production of Graphite in the United States.—Large amounts of graphite are used in the United States annually, but the amount produced falls far short of the demand. The country produced 5,611 tons in 1928, which was 24.2 per cent of the total amount used.¹ The imports of graphite in 1928 amounted to 17,569 tons, valued at \$801,559. Graphite is made artificially by the Acheson Graphite Company at Niagara Falls, New York. In 1927, this company produced 6,128 tons, but its output fluctuates considerably from year to year. Fluctuation is equally true of the world's production of natural graphite. This production averages 100,000 metric tons annually, of which the United States uses about one-fifth.

Selected Readings on Graphite

There is an abundance of literature on graphite. The bibliographies in Ries' "Economic Geology" and Ladoo's "Non-Metallic Minerals" should be consulted for more references.

FERGUSON, GROUT, and DUB: Graphite, Spurr's "Political and Commercial Geology," pp. 373-379, McGraw-Hill Book Company, Inc., New York, 1925.

LADOO, R. B.: "Non-Metallic Minerals," pp. 258-280, McGraw-Hill Book Company, Inc., New York, 1925.

LINDGREN, WALDEMAR: "Mineral Deposits," pp. 820-827, McGraw-Hill Book Company, Inc., New York, 1928.

¹ U. S. Bur. Mines,

RIES, H.: "Economic Geology," pp. 344-354, John Wiley & Sons, Inc., New York, 1925.

SPENCE, H. S.: Graphite, Canada Dept. Mines, Mines Branch, *Bull.* 511, 1920. A very fine account of graphite.

U. S. Mineral Resources for 1913, 1914, 1918, and 1919 contain good accounts of graphite and also bibliographies.

MICA

Mica is a mineral possessing several important physical properties which make it indispensable in the electrical industry. It is familiar to all as the transparent material used in the front of stoves and in lamps. It is erroneously called "isinglass," which is a gelatin made from the viscera of certain fish.

The Mica Minerals and Their Composition.—There are three important varieties of mica, but only two are extensively utilized. These three are (in the order of their economic importance):

Muscovite (white mica), $\text{H}_2\text{KAl}_3(\text{SiO}_4)_3$.

Phlogopite (amber mica), $(\text{K}, \text{H})_3\text{Mg}_3\text{Al}(\text{SiO}_4)_3$.

Biotite (black mica), $(\text{K}, \text{H})_2(\text{Mg}, \text{Fe})_2(\text{Al}, \text{Fe})_2(\text{SiO}_4)_3$.

Physical Properties of Mica.—The value of mica lies in its marvelously perfect cleavage, flexibility, elasticity, non-conductivity, infusibility, and lustrous cleavage faces. No other mineral has a more perfect cleavage. Large quantities, in sheets 0.001 inch in thickness, are sold annually. The experienced splitter can make perfect sheets of mica 0.0001 inch thick. If the mechanical difficulties could be overcome, even thinner sheets could be produced. The flexibility of mica makes it possible to roll a sheet 0.001 inch thick into a cylinder 0.25 inch in diameter, and its elasticity would permit flattening it out again. The fact that mica is a perfect non-conductor of electricity makes it indispensable in the electrical industry. All attempts to produce a non-conductor that could be substituted for mica have been unavailing. Mica is likewise a non-conductor of heat and is used for heat insulation. Its infusibility is, of course, also important in the last-mentioned use. The mineral may be perfectly transparent, or it may be opaque. The cleavage faces of the mica sheet have a brilliant luster, and this makes possible the use of mica for decorative purposes.

This combination of splendidly developed physical properties has placed mica in the front rank of the indispensable minerals. In the electrical industry, it is just as important as copper.

Mode of Occurrence of Mica.—Mica is of extremely widespread occurrence, being found in all types of rocks, but nearly always in limited amounts. As a rule, it occurs as small crystals (flakes), which rarely attain a diameter of half an inch.

The mica of commerce occurs in the pegmatites dikes (see Fig. 244, p. 606) that furnish feldspar, quartz, and other minerals. As was noted

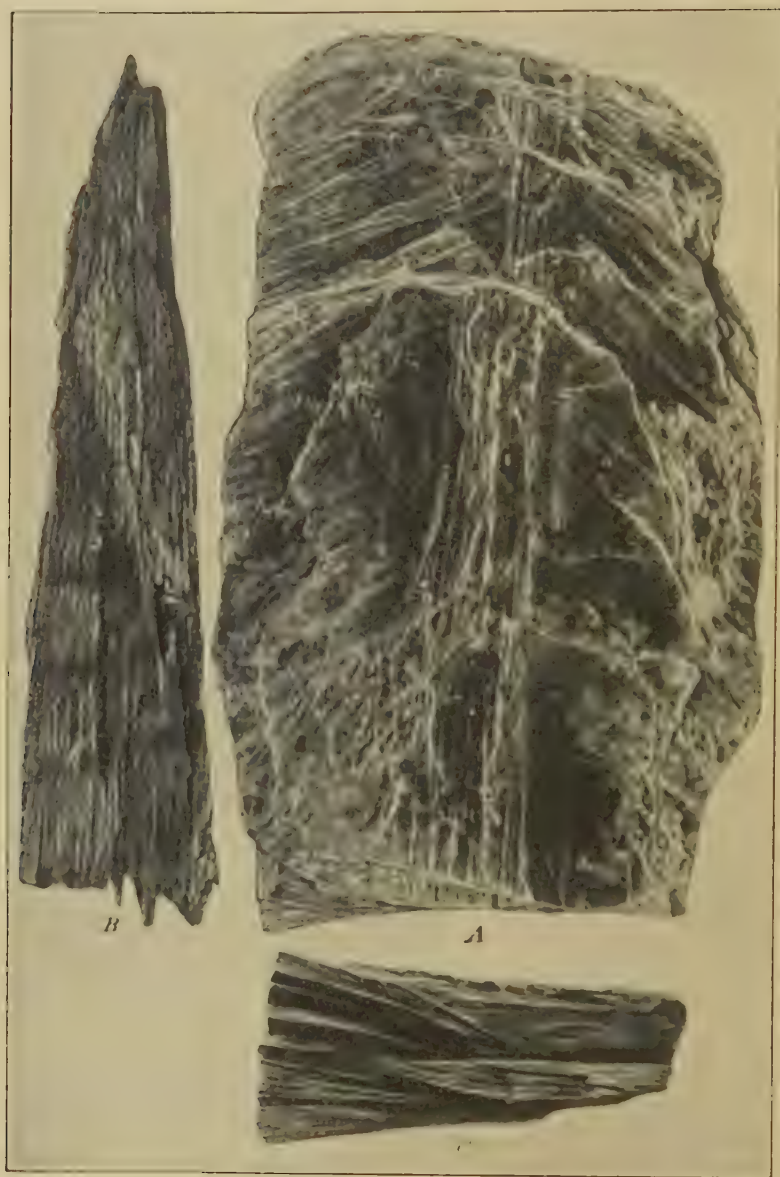


FIG. 248.—Muscovite from Topsham, Maine, showing wedgelike form of mica books and herring-bone structure (A). A, front view. B, side view. C, end view. Natural size. (Bastin, *U. S. Geol. Survey Bull.* 445, pl. 19.)

under Feldspar, the most striking feature of these dikes is the large size of the crystals composing them. Mica crystals 12 feet across have been reported¹ from the Transvaal, South Africa. A single mica crystal weighing 4,332 pounds was found in 1926 in the mine of the Spruce Pine Mica Company in North Carolina. As a rule, however, these large crystals are rare, and about 90 per cent of them are unsuited for splitting into sheets.

The large mica crystals are commonly called "books," because the edges of the crystals showing the cleavage planes resemble the pages of a book (Fig. 248 *B*). The mica crystals commonly have a wedgelike form as they occur in the vein (see Fig. 248 *B*). In massive deposits, these wedgelike books interlock in a most intricate manner.

The occurrence of mica in the pegmatites is very irregular. A large and easily worked mass may change rapidly to a few scattered patches. There is little to guide the miner in locating the workable areas.

Origin of Mica.—Mica is a common original constituent of many kinds of igneous rocks, which shows that it forms under the same conditions as the other minerals. The pegmatites are formed from solutions rich in mineralizers, a fact which favors the large growth of the constituent minerals. The development of large mica crystals takes place along with that of the other constituents. Both muscovite and biotite occur in the typical granitic pegmatite, but only the muscovite (because of its color and superior qualities) is mined. Phlogopite (of higher magnesium content) is associated with basic igneous rocks, crystalline dolomite, and serpentines. All these rocks contain magnesium, and the occurrence of phlogopite in them illustrates the genetic relationship existing between a rock type and the minerals in it.

Distribution of Mica in the United States.—Mica deposits occur in those regions where granitic rocks are abundant, for pegmatites are found only in association with such rocks. Such an area extends from *Maine to Alabama*, an area responsible for 95 per cent of the mica production of the United States. *Central Texas, Wisconsin, Minnesota*, the *Black Hills of South Dakota*, and numerous localities all over the west have deposits of mica.

Foreign Mica Deposits.—The largest *muscovite* deposits in the world are in *India*. This country supplies about 65 per cent of the world's needs. The mines have been worked a long time, and the workmen are highly skilled, with the result that a very high-grade product is put on the market. *Bengal and Madras* are the chief areas of mica production.

Canada possesses the only important mines of *phlogopite* in existence and so is the chief source of this valuable type of mica. The deposits are in southern *Quebec* (just north of *Ottawa*) and in *Ontario* (southeast of *Ottawa*).

¹ LINDGREN, WALDEMAR, "Mineral Deposits," p. 848.

Preparation of Mica for Use.—The mica, as it comes from the mines, must be cleaned, split and sorted, and roughly trimmed. Most of the material in a mine has imperfections, such as inclusions of other minerals, poor color, and rumped, broken, or strained crystals. Hardly 10 per cent, therefore, of the material mined can be manufactured into sheets. After being cleaned, the mica is split into sheets $\frac{1}{16}$ inch thick, sorted by sizes, and roughly trimmed to remove poor material along the edges. The minimum size of mica sheets put on the market is 1.5 by 2 inches, and to cut these out, pieces of mica double that size (3 by 4 inches) must be used. This finished product is called "punched mica," because the cutting is done with a punch. Mica is very easily cut into any desired form so is especially adaptable for use as the irregular shapes that must be cut for various heating elements. For some uses, unusual sizes of mica sheets are required. These are called "extra extra special" grades and are 8 by 10 inches.

Uses of Mica.—The chief use of mica is in the *electrical industry*. It is employed in telephones, dynamos, condensers, lightning arresters, commutators, light sockets, and many other types of equipment. Large quantities are used in making household appliances. The phonograph industry formerly required large amounts of mica, but the radio has caused a great decline in the production of phonographs. Some high-grade mica is used in condensers for radios. A small amount is used in head phones and loud speakers. Phlogopite is softer than muscovite (which is the chief mica of commerce), and it is thus particularly suitable for separating the segments of a commutator, as the metal bars and the phlogopite wear at the same rate.

As a *heat-insulating material*, mica is used in lamp chimneys for gas and gasoline lamps, in optical lanterns, and in electrical heating appliances. A very common use of the mineral is in the fronts of stoves and lanterns, for spectacles and lamp shades, and as a substitute for glass in windows where glass might be broken.

The mica unsuited for manufacture into sheets is used for a great many purposes. It is *ground* to various sizes: from very small to 200-mesh sizes. For most purposes, it must be free from impurities. This ground material may be mixed with shellac, pressed, and molded into all sorts of forms. Ground mica is used on wall paper; as Christmas-tree snow; for sprinkling on roofing materials; in concrete; as a lubricant (in greases or alone), a tire powder, and a rubber filler; by artists as a material on which to paint pictures; and in other ways.

Production of Mica in the United States.—The United States produced 1,512,492 pounds of sheet mica, valued at \$212,482, in 1927 and imported 3,459,647 pounds, valued at \$1,630,309. The production of scrap or ground mica in 1927 amounted to 6,280 tons, valued at \$110,-

139. The domestic production and the imports of mica vary surprisingly from year to year.

New Hampshire produced 48 per cent and *North Carolina* 44 per cent of the mica output of the United States in 1927. The remaining 8 per cent came from *Alabama, Colorado, Connecticut, Georgia, Maine, Nevada, New Mexico, South Carolina, South Dakota, and Virginia*. Much mica is produced as a by-product in the mining of feldspar; hence, the states that produce feldspar are also producers of mica. This is a rather fortunate arrangement, because many pegmatites could not be worked for mica alone, even though it was abundant in them. Some ground mica is produced from mica schists, and a little has been recovered from kaolin-washing operations.

Selected Readings on Mica

- DE SCHMID, H. S.: Mica, Its Occurrence, Exploitation, and Uses, 2d ed., Canada Dept. Mines *Bull.* 118, 1912.
- LADOO, R. B.: "Non-Metallic Minerals," pp. 347-363, McGraw-Hill Book Company, Inc., New York, 1925. Contains bibliography.
- MYERS and STODDARD: Mica, *U. S. Mineral Resources*, 1925, Part 2, pp. 181-193.
- RIES, H.: "Economic Geology," pp. 364-370, John Wiley & Sons, Inc., New York, 1925.
- SCHALLER, W. T.: Mica, *U. S. Mineral Resources*, 1918, Part 2, pp. 629-694. Contains bibliography for other years, also.
- STERRETT, D. B.: Mica Deposits of the United States, *U. S. Geol. Survey Bull.* 740, 1923.

MINERAL FILLERS

Many products are manufactured which make use of some finely ground, inert earth material as a filler. The material is selected to fit the needs of the particular product. The need may be to give body or opacity, to absorb dyes or coloring pigments, or to give a smooth glazed surface to the product. For some products, fillers are used to add weight. These fillers are not necessarily adulterants, for they may replace a portion of the other material without affecting its properties.

The fillers undergo a minimum of preparation for use, largely because of their low value and because simply grinding and sizing are sufficient. Where possible, a material from a nearby source is used.

The list of materials employed as fillers is a long one, and their list of applications is even longer, for one material may be used in many different products. Ladoo has compiled a list of materials used as fillers and also a list of products and processes in which fillers are used. It is of value to group together earth materials having similar uses, and therefore Ladoo's lists are given here:

NATURAL MINERAL FILLERS

"Aluminum flake" (clay).	Magnesite.
Anhydrite.	Marble dust.
Apatite.	Mica.
Asbestos powder.	Ocher and umber.
Asbestine (talc).	Pumice.
Barite.	Pyrophyllite.
Bentonite.	Rottenstone.
Calcite.	Sand.
Celestite.	Serpentine.
Chalk.	Shale.
Clay.	Silica.
Coal (powdered).	Slate flour.
Diatomaceous earth.	Soapstone.
Dolomite.	Sulfur.
Feldspar.	Talc.
Flint.	"Talcene" (red shale).
Fullers' earth.	Tripoli.
Graphite.	Whiting.
Gypsum.	Terra alba (ground gypsum).
Iron oxides.	
Limestone.	

MANUFACTURED FILLERS

Blanc fixe (artificial BaSO_4).	Pearl filler.
Calcium sulfate.	Pearl hardening.
Carbon black.	Portland cement.
Flake white (variety name for basic carbonate or white lead).	Satin white.
Lime (hydrated).	Sublimed white lead (basic sulfate).
Lithopone.	White lead (basic carbonate).
Magnesia alba (basic magnesium carbonate).	Zinc oxide.

PRODUCTS AND PROCESSES IN WHICH FILLERS ARE USED

Artificial stone.	Insulating compounds.	Plasters.
Asphalt surfacing.	Leather.	Polishes.
Cements.	Linoleum and oilcloth.	Pressed and molded goods.
Ceramics.	Lubricants.	Putty.
Cordage.	Matches.	Roofing materials.
Dry batteries.	Oxychloride cement.	Rubber.
Dynamite.	Paint.	Soap.
Fertilizers.	Paper.	Textiles.
Flooring compounds.	Phonograph records.	Tooth powder and paste.
Foundry facings.	Pipe coverings.	Wood finishing.
Insecticides.		

Selected Readings on Mineral Fillers

- LADOO, R. B.: "Non-Metallic Minerals," pp. 364-367, McGraw-Hill Company, Inc., New York, 1925.
- WEIGEL, W. M.: Non-Metallic Mineral Filler Industry, *Am. Inst. Min. and Met. Eng. Bull.* 1,144-M, February, 1922.

—: Size and Character of Grains of Non-Metallic Mineral Fillers, U. S. Bur. Mines Tech. Paper 296, 1924.

PYROPHYLLITE

Pyrophyllite is a hydrous aluminum silicate, $\text{H}_2\text{Al}_2(\text{SiO}_3)_4$. It closely resembles talc, being a soft, light-colored mineral with a greasy feel and a foliated, fibrous, or massive form. Pyrophyllite occurs in beds or lenses in metamorphic rocks.

The principal deposits of pyrophyllite in the United States are in Moore and Chatham counties in *North Carolina*, but it occurs also at Chesterfield, Chesterfield County, *South Carolina*, and at Graves Mountain, Lincoln County, *Georgia*. A deposit at Hemp, Moore County, *North Carolina*, has been worked for years.

Pyrophyllite may be used for the same purposes as talc; in fact, it is commonly called "talc," and its production figures are included with those of talc and soapstone. It is used extensively for making crayons, pencils, and carved figures.

QUARTZ

Quartz is one of the extremely common minerals. It is what is known as a "persistent" mineral, for it occurs in all kinds of rocks and veins and from the surface of the earth to great depths. Its hardness, lack of cleavage, and insolubility favor its concentration at the surface, and hence it occurs abundantly as the chief constituent of sand and gravel. Quartz is of interest, also, because of its numerous varieties, many of which are prized for their color and used for gems.

Composition and Physical Properties of Quartz.—Quartz is silicon dioxide, SiO_2 . It has a hardness of 7 (scratches glass easily), no cleavage, an uneven to conchoidal fracture, and a vitreous to greasy or waxy luster. It ranges from perfect transparency to opaqueness and possesses nearly every color. Quartz occurs as crystals and in a dense form known as "cryptocrystalline." These dense varieties are really crystalline, but the particles are too small to be visible to the naked eye. The members of these two groups are listed in the table on page 624.

Mode of Occurrence of Quartz.—To enumerate all the modes of occurrence of quartz is to describe all the ways in which minerals can occur. The crystalline varieties of quartz are found in *igneous rocks*, in *cavities in all sorts of rocks*, and in *veins*. The cryptocrystalline forms occur in *veins* and in *cavities near the surface*.

Uses of Quartz.—Quartz has been mentioned many times on the preceding pages. It was noted as a constituent of *sandstones*; of *sand and gravel* in building materials; as a material used in the manufacture of *clay products*, *glass*, *sand-lime brick*, *mineral paints*, and *abrasives*. Likewise, its use as a *gem* and as a *refractory* was noted.

TABLE 124.—THE VARIETIES OF QUARTZ

Crystalline		Cryptocrystalline	
Name	Color	Name	Color
Rock crystal	Transparent	Chalcedony	White, grayish, blue, green, and other shades
Star quartz	Whitish radiating lines in transparent crystals	Carnelian or sard (chalcedony)	Clear red
Amethyst	Purple	Chrysoprase	Apple green
Rose quartz	Rose-red or pink	Prase	Dull leek-green
Citrine (false topaz)	Yellow	Plasma	Bright green to emerald-green
Smoky quartz or cairngorm	Smoky yellow to brown	Bloodstone or heliotrope	Green with spots of red (jasper)
Milky quartz	Milk-white	Agate (variegated chalcedony)	All colors, in bands or irregular
Rutilated quartz	Crystals of red rutile in transparent or white quartz	Moss agate (dendritic forms in chalcedony)	Dark gray
Cat's-eye or tiger-eye	Opalescent	Mocha stone (dendritic forms in chalcedony)	Dark gray
Aventurine quartz (contains scales of mica or hematite)	Glistening	Onyx (banded agate, but layers straight)	All colors
Sapphire	Blue	Sardonyx	Red layers (sard) with other colors
		Jasper (chalcedony)	Dull red, yellow, and brown
		Jasper agate (jasper with veins of chalcedony)	All colors
		Chert (chalcedony)	White and light gray
		Flint (chalcedony)	Dark gray to black
		Hornstone	Dark gray
		Siliceous sinter	White

Use as Ornaments.—Most of the varieties of quartz of satisfactory color are used for jewelry and ornaments. Beautiful vases and other art products have been carved from many of the varieties. Crystal balls are cut from rock crystal. A crystal ball in the National Museum at Washington, District of Columbia, is 30 inches in diameter and weighs 130 pounds. The rock crystal for this ball was found in Burma, cut in China, and polished in Japan.

Special Uses.—There are many special uses of quartz. One is in preparing thin, wedged-shaped plates for use in petrographic microscopes. Another is in radio sets. For this use, sections of quartz are cut lengthwise from a crystal and help to eliminate loud noises by maintaining a uniform frequency.

REFRACTORIES

The requirements of modern, high-temperature metallurgical processes have created a demand for a furnace lining that not only *will withstand high temperatures* but also *will not react with the material in the furnace*. Further requirements of materials for these linings are the *ability to withstand rapid changes in temperature without cracking and spalling*, *sufficient strength to withstand the wear of metals or slag*, and the *capacity of being molded into bricks and other forms*.

Materials that will withstand high temperatures are more numerous than many would suppose. A list of such substances, both natural and artificial, that are used at present (1928) includes the following:

- Andalusite.
- Bauxite.
- Chromite.
- Diaspore.
- Dolomite.
- Dumortierite.
- Graphite (natural and artificial).
- Magnesite.
- Quartz, ganister, silica brick.
- Silicon carbide or carborundum (artificial).
- Sillimanite (artificial).
- Spinel (artificial).
- Zircon and baddeleyite.

All these materials are excellent refractories, but each is selected for the particular use for which it is best suited.

Andalusite.—Andalusite is an aluminum silicate, Al_2SiO_5 . It is usually slightly impure. At $1,390^\circ\text{C}$., it is transformed into sillimanite and thereafter, of course, has the same melting point ($1,816^\circ\text{C}$.).

Andalusite is found in metamorphic rocks. It commonly occurs as isolated crystals but also as coarsely granular masses, which are, of course, the chief source of the economic product.

The only deposit of andalusite worked in the United States at present is near Mocalno, Mono County, *California*. This deposit is on the southwestern slope of the White Mountains, at an elevation of 10,000 feet. It is a large deposit, and the ore averages between 75 and 85 per cent andalusite. The ore is shipped to the Champion Porcelain Company at Detroit, Michigan. The andalusite is ground to pass a 300-mesh screen, is fused, and used in making spark plugs. This fused product is

composed of sillimanite, because the andalusite becomes sillimanite at the furnace temperatures. The product is very strong, is a poor conductor of electricity, and has a low coefficient of expansion.

Bauxite.—Bauxite is a hydrous aluminum oxide; and, although it is not regarded as a mineral, it has a composition approximating $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$. This composition represents 73.9 per cent alumina. Bauxite loses its water at high temperatures, and the resulting oxide melts at 1,880 to 2,050°C. (3,722°F.). Bauxite is a massive, earthy mineral usually showing a pisolitic structure.

Bauxite occurs as masses in mantle rock; interbedded with clays; and in veinlike deposits. *Arkansas* furnishes 90 per cent of the bauxite mined in the United States; the remainder comes from *Georgia*, *Alabama*, and *Tennessee*.

High-alumina refractories are made from bauxite. These are prepared by calcining the bauxite, adding a clay binder, molding into bricks, and firing. As a rule, these bricks fuse at a lower temperature than the melting point of alumina, because of impurities present. They are used especially for lining open-hearth steel (and other) furnaces. These brick are chemically inert.

Only 160 tons of bauxite was used in the United States in 1927 for making refractories, as diaspore clays which are higher in alumina are much more extensively used (see *Diaspore*, below).

Chromite.—Chromite is FeCr_2O_3 . It has a melting point of 2,180°C. (3,956°F.), which makes it one of the best refractory substances known. It is black. It occurs as crystals, veins, and tabular masses in the basic igneous rocks peridotite and dunite and in their common alteration product serpentine.

The United States imports essentially all its chromite. *California* and *Maryland* make a small production (660 long tons in 1928).

The chief use of chromite is in refractories. In 1925, 41 per cent of the total used in the United States was employed for that purpose, and its use has greatly increased since then, though the actual figures are not available. In 1926, some manufacturers of chromite brick reported a 500 per cent increase in their sales of these refractories. About 88 per cent of the chromite used as refractories in 1925 was used in making brick; 10 per cent for cement; and 2 per cent as lump ore. Chromite brick are regarded as essential in steel furnaces. They are placed at the slag line in the furnace; magnesite brick are put on the bottom; and silica-alumina brick on the sides and top. The chromite brick resist corrosion by the slag and metal better than the other brick, and they stand temperature changes better. They are also slightly cheaper than magnesite brick. About 2.5 pounds of chromite is used per ton of steel produced. Chromite brick are also used as lining in furnaces for smelting copper and nickel.

Diaspore.—Diaspore is $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, and it contains about 85 per cent alumina. The melting point is the same as that of bauxite. Diaspore occurs as oolites in clay or as a massive, porous, rough rock.

The production of diaspore in the United States comes entirely from the north-central Ozark area in *Missouri* (see Diaspore, p. 600). The material is well suited for use as high-alumina refractories (containing over 58 per cent alumina) and finds its chief market for that purpose. Brick made from diaspore withstand temperatures of $1,850^\circ\text{C}$. or higher. In 1927, 40,085 tons of diaspore clay was used in the United States in making refractory brick (160 tons of bauxite was so used that year).

Dolomite.—Dead-burned dolomite is now extensively employed for lining basic open-hearth furnaces, in amounts far in excess of the amount of magnesite so used.

Dumortierite.—The formula for dumortierite is $\text{Al}_3\text{HBSi}_3\text{O}_{20}$. It is a blue mineral; has a hardness of 7; and is found in pegmatites, gneiss, granite, and other rocks. It occurs in *Arizona*, *Washington*, and *California*. It changes to sillimanite (or possibly to mullite) at high temperatures, and its uses are similar to those of andalusite and sillimanite.

Graphite.—Graphite is being replaced as a refractory by other materials.

Magnesite.—Magnesite as a refractory has been discussed under Magnesite (p. 586).

Quartz, Ganister, Silica Brick.—"Ganister" is a name applied to crushed quartz or quartzite. This material and a small amount (about 2 per cent) of lime are ground together and then molded into bricks and burned. The brick are superior to most fire brick, because of their greater strength. They are extensively used in all types of furnaces. In 1928, 245,881,000 silica brick, valued at \$12,750,000, were made in the United States.

Silicon Carbide or Carborundum.—Carborundum is a product of the electric furnace and has a very high melting point. It is a very satisfactory refractory material and is used for somewhat the same purposes as high-alumina brick.

Sillimanite.—Sillimanite has the same composition as andalusite and kyanite but differs from them in that it is more stable at high temperatures. It melts at $1,816^\circ\text{C}$. ($3,300^\circ\text{F}$.). It is commonly associated with andalusite and kyanite and is a constituent of many kinds of metamorphic rocks. Workable deposits of sillimanite are unknown, but it can be made artificially from diaspore clays or bauxite ore. The common method of its manufacture, however, is to mix the proper amounts of silica and alumina and fuse in an electric furnace.

The chief use of sillimanite is in making spark plugs. It is also made into a strong, neutral refractory brick.

Spinel.—Spinel is $\text{MgO} \cdot \text{Al}_2\text{O}_3$. It is very hard and occurs as crystals in metamorphic rocks. Its melting point is high ($2,117^\circ\text{C}.$) if the material is pure. It does not occur in sufficient quantities to be used as a refractory, but a company in Los Angeles, California, has been able to produce it artificially by fusing calcined magnesite and alumina in an electric furnace. It can be made into brick just as the other refractory materials are.

Zircon and Baddeleyite.—Zircon is ZrSiO_4 , and baddeleyite is ZrO_2 . Both minerals have a very high melting point: zircon melts at $2,550^\circ\text{C}.$ ($4,622^\circ\text{F}.$), and baddeleyite at $2,500$ to $2,950^\circ\text{C}.$ ($5,342^\circ\text{F}.$). The two minerals occur in minor quantities in igneous rocks, but the commercial materials are found in sands and gravels.

Brazil is an important producer of zircon and baddeleyite. None of the ore was imported into the United States in 1926, and only 2 tons in 1927. The chief source of these minerals in the United States is the beach sands about 4 miles south of Pablo Beach in Duval and St. John counties, *Florida*. From 10 tons in 1922, the production in this locality rose to 3,646 tons in 1927. By special treatment, the zircon can be converted into zirconia crucibles that withstand temperatures as high as $2,300^\circ\text{C}.$ ($4,352^\circ\text{F}.$). These crucibles are nearly pure zirconia (ZrO_2) and have been used for melting platinum at a temperature of $1,755^\circ\text{C}.$ and rhodium at $1,950^\circ\text{C}.$

Selected Readings on Refractories

Few articles deal specifically with refractories. See bibliographies cited under previous discussions of most of the materials listed above.

Zircon: H. C. Morris, Spurr's "Commercial and Political Geology," pp. 209–216, 1920.

R. B. Ladoo, "Non-Metallic Minerals," pp. 657–665, McGraw-Hill Book Company, Inc., New York, 1925.

Andalusite: Ladoo, *Idem.*, pp. 39, 40.

Sillimanite: *Opus cit.*, pp. 527–529.

Spinel: *Opus cit.*, pp. 578, 579.

Chromite: See *U. S. Mineral Resources and Mineral Industry*.

SEPIOLITE OR MEERSCHAUM

Sepiolite is a tough, compact, earthy mineral that is highly prized by smokers for pipes and cigar holders. It is a hydrous magnesium silicate, $\text{H}_4\text{Mg}_2\text{Si}_2\text{O}_{10}$. It is usually white but may be yellowish or reddish. Sepiolite may be granular, earthy, or fibrous in structure. The mineral, as mined, is soft, being easily indented with the finger nail. After being dried, it becomes harder and is pure white. It is then so light that it will float on water; hence, the German name *meerschaum*, meaning "sea foam."

Mode of Occurrence and Distribution of Sepiolite.—Sepiolite occurs in alluvial deposits and in veins in limestones. It is found as masses of

all shapes and sizes. The best known deposits are near Eskişehir, *Brusa*, Asia Minor, where the material is said to have been quarried for 2,000 years. The sepiolite occurs as nodules some of which are as large as footballs. The nodules are in alluvial clays. Other deposits occur in *Spain*, *Greece*, and *Czechoslovakia*.

Sepiolite is found in small amounts in several places in the United States, but only the two deposits in *New Mexico* are important. These are along the valley of the Gila River in northwestern Grant County. The sepiolite occurs in veins in limestone, along with chert, quartz, calcite, and clay.

Uses of Sepiolite.—The only use of sepiolite is for making smoking articles. The material, after being mined, cleaned, and dried (which hardens it), is cut into the desired shape, waxed, and polished. The color produced by the reaction of nicotine with the wax is prized by the smoker. No figures as to the production of sepiolite are available.

Selected Readings on Sepiolite

LADOO, R. B.: "Non-Metallic Minerals," pp. 343-346, McGraw-Hill Book Company, Inc., New York, 1925.

RIES, H.: "Economic Geology," pp. 363-364, John Wiley & Sons, Inc., New York, 1925.

TALC (STEATITE) AND SOAPSTONE

Talc usually occurs as aggregates of folia, but it may also be massive and is then known as "steatite." The coarsely crystalline massive material is called "soapstone."

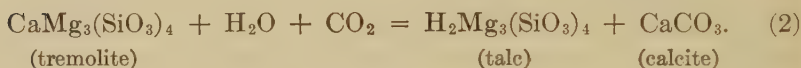
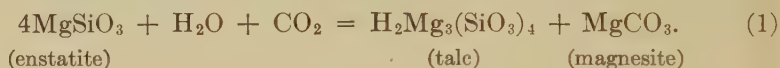
Steatite and soapstone were used by the men of the stone age, who, on account of the softness of the minerals, were able to carve many different objects from them. Later, the fire-resisting qualities of soapstone were discovered, and it was used in making pots; hence, the name "potstone," sometimes still applied to soapstone.

Composition of Talc.—Talc is a hydrous magnesium silicate, $\text{H}_2\text{Mg}_3(\text{SiO}_3)_4$. A little chlorite is probably present in most talc, as analyses show some alumina and ferrous iron. Nickel is sometimes present, also.

Physical Properties of Talc.—Talc is a soft, micaceous mineral, having a hardness of one. The presence of impurities increases its hardness, and so does drying. Talc is pure white, gray, many shades of green, and rarely red or brown. It is usually foliated, but it also occurs in fibrous, granular, and massive forms. The remarkable greasy feel of the mineral is due to its micaceous character and softness, which permits the scales to glide over one another easily. Many of the uses of talc are due to this property. Talc is a poor conductor of heat and electricity. It is fire resistant, is not affected by rapid changes of temperature, and is insoluble. This combination of physical properties makes it useful for a wide range of purposes.

Mode of Occurrence of Talc.—Talc and soapstone commonly occur as *lenses* of varying thicknesses *interbedded with limestones, dolomites, schists, and gneisses*; or as *massive aggregates associated with basic igneous rocks*, such as peridotite and dunite. The massive soapstone is usually found along the margin of the igneous mass. The lenses of talc are commonly called “veins,” but they are not veins.

Origin of Talc.—The composition of talc gives at once a clue to its origin. It was derived from a magnesium rock of some type. Dolomite is the common magnesium sedimentary rock, and most of the purer talc deposits are found in association with dolomite or marble (limestone). The original dolomite may have been siliceous, or silica may have been introduced during the metamorphism which developed such magnesian silicates as enstatite, MgSiO_3 , and tremolite, $\text{CaMg}_3(\text{SiO}_3)_4$. These silicates were then altered to talc as follows:



That reaction (1) probably took place is evidenced by the fact that breunnerite, which is an iron-rich variety of magnesite, occurs with talc. In some deposits of talc, the mineral occurs as a fibrous pseudomorph after tremolite, which is the reason for writing reaction (2).

The magnesium-rich silicates of peridotites and other basic rocks can be altered into talc and soapstone in the same manner. The occurrence of talc as a pseudomorph after many of the silicates is sufficient evidence of this type of origin. Many soapstone deposits probably originated in this way, and the aluminous materials of the original rock formed the chlorite, mica, and other impurities of the soapstone. The foliation of talc has evidently been caused by earth movements.

Distribution of Talc in the United States.—Talc deposits are widely distributed over the United States, as the accompanying map (Fig. 249) shows. The production comes from California, Georgia, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Vermont, and Virginia.

California produces excellent talc. The deposits are at Lindsay, Tulare County; Zabriskie, Keller, and Tecopa, Inyo County; Riggs, Avawatz, Acme, and Silver Lake, San Bernardino County; Schilling, Shasta County; and Latrobe, Eldorado County.

The talc deposits of *New York*, which is the leading producing state, are at Gouverneur, St. Lawrence County, and near Natural Bridge, Lewis County. The New York talc is mostly of the fibrous variety and is very pure.

Vermont has enormous deposits of talc and soapstone. They are found at Johnson, Lamoille County; Chester and Rochester, Windsor County; Waterbury, Washington County; East Granville, Addison County; and Windham, Windham County.

Massive soapstone and talc deposits occur in Nelson, Fairfax, Franklin, and Albemarle counties in *Virginia*. Undeveloped deposits are found in Campbell, Bedford, Amelia, Grayson, Carroll, and other counties.

The *North Carolina* deposits of talc are at Kinsey and Marble, Cherokee County; Marshall, Madison County; Candler, Buncombe County; Nantahala and Hewitts, Swain County; and Beta, Jackson County.

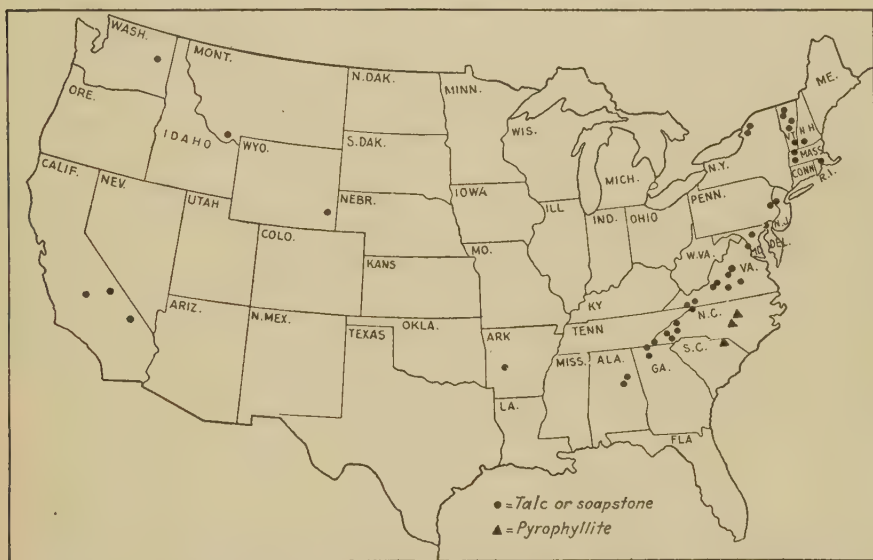


FIG. 249.—Map showing the location of the most important deposits of talc and soapstone and pyrophyllite in the United States.

Talc and soapstone are abundant in many other countries, although none produces so much as does the United States.

Preparation of Talc for Use.—Most talc is put on the market in ground form, but many products are sawed or machined from the massive material. The ground talc must be carefully graded for the various uses. The rock is usually ground to pass a 200-mesh screen.

Uses of Talc.—Talc and soapstone have an extraordinarily long list of uses. Ladoo, in his report, has a list covering four and a half pages. In none of these uses, however, is talc an absolutely essential substance.

The major uses for *ground talc*, as given by Ladoo,¹ are in paper manufacture (filler, glazing, blotting papers); in roofing-paper manufacture;

¹ For details, see his bulletin.

in textiles (dressing, coating, dyeing); in rubber (filling, dusting, protective coating); in paints (many uses); in soap manufacture (filler); for foundry facing; in toilet preparations (talcum powders, face powders, creams, pastes); for wire insulation; in lubricants (alone or with greases); in linoleum and oil cloth; for pipe coverings; in pottery and porcelain; for electrical insulation (so-called "lava," which is a baked form that is hard and resistant and makes an excellent insulator); in rope and twine; in leather manufacture; in the glass industry (for polishing plate glass and dusting glass molds); in wall plaster; in asbestos products; as imitation stone; in dyeing; and a great many other uses.

The *massive talc and soapstone* are cut into a multitude of forms. Some of the uses are as lava blanks for electrical insulation, gas burner tips, and spark plugs; crayons and pencils (a large and important use); tailors' chalk; molds for casting glass bottles, watch glasses, and various metals; refractory brick and blocks; for polishing and carving (especially by Chinese); and for making cooking utensils (by primitive people). Soapstone slabs are used for electrical switchboards and base plates, acid-proof laboratory tables, sinks, hoods, and tanks; laundry tubs and sinks; fireless-cooker stones; foot warmers; and griddles.

Production of Talc in the United States.—The United States produces a large amount of talc and soapstone (about one half of the world's production). The production in 1927 amounted to 192,316 tons (of all kinds), valued at \$2,234,624. The imports for the same year, largely from Canada, Italy, and France, were 25,194 tons, valued at \$550,382. Of the domestic production, 96 per cent of the material was ground.

Selected Readings on Talc and Soapstone

- LADOO, R. B.: Talc and Soapstone, *U. S. Bur. Mines Bull.* 213, 1923. Excellent account of mining, milling, and uses.
- : "Non-Metallic Minerals," pp. 616-628 (talc); pp. 554-557, (soapstone), McGraw-Hill Book Company, Inc., New York, 1925.
- MCGURK, P. A.: Talc and Soapstone, *Mineral Industry*, 1926, pp. 642-649.
- RIES, H.: "Economic Geology," pp. 407-412, John Wiley & Sons, Inc., New York, 1925. Contains bibliography.
- STODDARD, B. H.: Talc and Soapstone, *U. S. Mineral Resources*, pp. 201-211, 1925. Contains bibliography.

TRIPOLI

Tripoli is a siliceous rock which at the time of its discovery was thought to be diatomaceous earth. Diatomaceous earth was called "tripolite" at that time, and tripoli retains a form of the name. Tripoli, however, does not contain diatoms, the identification of which is an easy method of distinguishing between the two substances. Tripoli, moreover, has a harsh feel, whereas diatomaceous earth feels smooth. The rottenstone of Pennsylvania is wrongly included with tripoli.

Composition and Physical Properties of Tripoli.—Tripoli is nearly pure silica, SiO_2 . It is soft and porous. It is usually white, buff, or tan but may be yellow or red. It occurs in massive form and shows a wide range in compactness, *i.e.*, from a soft, friable rock easily crumbled with the fingers to a hard, compact rock that must be crushed before it is used. Some tripoli is very absorbent; other varieties are not.

Mode of Occurrence of Tripoli.—Tripoli occurs as a residual bedded deposit associated with limestones. It occurs at or near the surface in most regions but may also lie under an overburden so thick as to require underground-mining methods. The thickness of overburden ranges from a foot to over 100 feet, depending upon the depth of the weathered zone.

Origin of Tripoli.—Tripoli is the result of the weathering of chert, cherty limestone, or other siliceous limestones.

The chert breaks down to a white, porous material, the chief change being a granulation, probably by the removal of the finest particles. The change produces a very small amount of hydrous, opaline silica. The alteration to tripoli is especially apt to develop in the outer part of a chert or flint nodule, where from 1 to 5 per cent calcium carbonate is usually present. The thin, white layer on the outside of flint and chert nodules is tripoli. Gradations of tripoli into chert are common in all deposits of the former.

The leaching of the calcium carbonate from a cherty or other siliceous limestone concentrates the silica and forms a residual deposit of tripoli.

Distribution of Tripoli in the United States.—The largest deposits of tripoli that are worked in the United States are in Missouri and Oklahoma and in Illinois. Other deposits are in Tennessee, Alabama, Georgia, and Arkansas. Some have been reported from Nevada.

The *Missouri-Oklahoma* tripoli deposits are near Seneca, Newton County, Missouri, and across the line in Ottawa County, Oklahoma. The beds are horizontal, range from 2 to 20 feet in thickness, and have an overburden averaging a thickness of 5 or 6 feet. The material is dominantly the soft, granular variety, but there are local areas of compact tripoli which is capable of being cut into filter blocks and other forms.

The *Illinois* deposits of tripoli are in Union and Alexander counties in southern Illinois. The production centers around Tamms and Elco. The tripoli occurs in large deposits, usually having a thick overburden. The material is more compact and harder than the Missouri tripoli and is not so absorbent. Unaltered chert is common throughout the deposit. The tripoli is used almost entirely as ground material.

The *Tennessee* tripoli deposits are at Black Fox in Bradley County. The material is thick and has a thin overburden (2 to 6 feet). It is milled, and various grades of ground tripoli are produced.

Other deposits are near Rome, Floyd County; Kingston, Bartow County; and Dalton, Whitfield County, *Georgia*; near Butterfield, Hot Springs County, *Arkansas*; in northeastern Calhoun County and at Riverton, Colbert County, *Mississippi*; and near Goldfield, Esmeralda County, *Nevada*.

Uses of Tripoli.—Ground tripoli is used for many of the purposes that are listed as the uses of silica. Tripoli is used as foundry facings, as a filler for rubber, in paints, in glass making, in pottery, and in enamels. As an abrasive, it is employed chiefly in polishes, soaps, and cleansers.

The Missouri tripoli is cut into filters of many shapes, of which cylinders and disks are common forms.

Production of Tripoli.—The annual production of tripoli in the United States is listed by the Bureau of Mines under Abrasives. The exact production figures for tripoli are not known, as the rottenstone of Pennsylvania is blanketed with it. The latest figures were given in the table under Abrasives (p. 598).

Selected Readings on Tripoli

LADOO, R. B.: "Non-Metallic Minerals," pp. 641-651, McGraw-Hill Book Company Inc., New York, 1925. Contains good bibliography.

PERRY, E. S.: Tripoli Deposits of Oklahoma, Okla. Geol. Survey *Bull.* 28, 1917.

SIEBENTHAL and MESLER: Tripoli Deposits near Seneca, Missouri, U. S. Geol. Survey *Bull.* 340-J, 1908.

INDEX

A

- Abrasives, artificial, 597
 - natural, 595
 - production, 598
 - selected readings, 598
 - uses, 301, 597
- Accessory minerals, 26, 27, 31
- Accumulation of petroleum, 406-418
- Acid phosphates, 560
- Actinolite, 532
- Adams, L. H., 19
- Adaville, Wyo., coal, 353
- Adirondack Mountains, N. Y., garnets, 596
 - magnetite, 104
- Agate, 624
- Agents of weathering, 59
- Ajo, Ariz., copper district, 178
- Alabama, barite, 581
 - bauxite, 301, 626
 - coal, 362
 - columbite, 329
 - fire clay, 471
 - graphite, 614
 - hematite, 99
 - lime, 521
 - limonite, 108
 - mica, 619
 - oil and gas, 439
 - pyrite, 543
 - tripoli, 633
- Alabaster, 8, 515
- Alaska, barite, 581
 - chromite, 117
 - coal, 364, 371
 - copper, 182, 183
 - gold, 256, 258
 - placers, 258
 - tin, 291
- Alberta, coal, 371
 - oil, 447
- Albite, 46, 50, 605
- Alclad, 304
- Algae, in coal formation, 348
 - in oil formation, 394
- Algeria, arsenic, 310
 - iron, 110
 - oil, 451
- Alluvial clays, 470
- Almaden, Spain, mercury district, 321
- Alsace, France, oil, 452
 - potash, 562
- Aluminum, ore minerals, 297
 - physical properties, 297
 - production, 304, 305
 - selected readings, 305
 - uses, 187, 302
 - (*See also* Bauxite.)
- Aluminum bronze, 187, 303
- Aluminum flake, 622
- Aluminum oxides, 65
- Alundum, 302, 597
- Alunite, 52, 55, 260, 562
- Amblygonite, 590
- Amethyst, 8, 610, 611, 624
- Ammonia, 381
- Ammonium sulfate, 381, 563
- Amosite, 532
- Amphiboles, 48
- Anaconda Copper Mining Company, 159, 162, 185, 228, 240, 560
- Andalusite, 79, 625
- Anderson, F. M., 394, 443
- Andesine, 605
- Andesite, 492
- Anglesite, 75, 199
- Angola, diamonds, 612
- Anhydrite, 515, 516, 548, 622
- Anorthite, 605
- Anorthoclase, 605
- Anthophyllite, 531, 532
- Anthracite, 343, 344, 362, 371
- Anthraxylon, 348
- Anticline, 409-415
- Antimony, domestic deposits, 306
 - foreign deposits, 307
 - mode of occurrence, 50, 52, 306

- Antimony, ore minerals, 306
 origin, 306,
 production, 309
 selected readings, 309
 uses, 307
- Apatite, 26, 33, 48, 104, 290, 622
- Appalachian region, coal field, 361
 iron, 108
 oil and gas field, 438
- Aquamarine, 46
- Argentina, bismuth, 311
 oil, 450
- Argentite, 52, 240, 259, 262, 267, 269, 276
- Arizona, abrasives, 596
 asbestos, 533
 barite, 581
 bentonite, 600
 bismuth, 311
 copper, 165, 170, 171, 172, 176, 178, 181
 dumortierite, 627
 feldspar, 606
 fluorite, 573
 fullers' earth, 608
 garnets, 612
 gold, 282
 gypsum, 516
 lead, 210
 manganese, 127
 mercury, 321
 molybdenite, 131
 onyx marble, 500
 peridot, 612
 silver, 266
 strontium, 591
 thenardite, 569
 tungsten, 139
 vanadium, 142
- Arkansas, abrasives, 596
 aluminum, 299, 626
 antimony, 307
 cadmium, 314
 coal, 363
 diamonds, 612
 gypsum, 516
 manganese, 127
 novaculite, 596
 oil and gas, 440
 phosphates, 559
 tripoli, 634
- Arkose, 500
- Arnold, Ralph, 443
- Arsenic, domestic deposits, 310
 foreign deposits, 310
 mode of occurrence, 26, 35, 50, 52, 309
 ore minerals, 309
 origin, 309
 production, 311
 selected readings, 311
 uses, 187, 310
- Arsenopyrite, 48, 50, 248, 278, 279, 290, 293, 309
- Artificial abrasives, 597
- Artificial coke, 376
 by-products, 378
 coking coals, 379
 manufacture, 377
 uses, 380
- Artificial gas, 381, 391
- Artificial graphite, 616
- Asbestic, 534
- Asbestine, 622
- Asbestos, 529
 cross fiber, 531
 deposits of Canada, 533
 deposits of United States, 532
 mass fiber, 531
 mode of occurrence, 531
 ore minerals, 531
 origin, 532
 physical properties, 529
 selected readings, 535
 uses, 526, 527, 534
- Asbestos powder, 622
- Ash in coal, 351
- Ashley, G. H., 352
- Aspen, Colo., gold-silver district, 268
- Asphalt, 528
 mode of occurrence, 383, 528
 origin, 528
 production, 528
 selected readings, 529
 uses, 528
- Assyrians, 11, 12
- Atacamite, 185
- Australia, bismuth, 311
 cadmium, 314
 chromite, 120
 coal, 371
 cobalt, 123
 copper, 186
 gold, 277
 iron, 110
 lead, 225

- Australia, molybdenum, 131
 osmiridium, 325
 sapphire, 610
 tantalum, 329
 tin, 293
 uranium and radium, 332
 zinc, 225
 Austria, graphite, 615
 iron, 110
 magnetite, 586
 mercury, 321
 Autunite, 331
 Aventurine, 624
 Azurite, 8, 75, 148, 165
- B
- Babbitt metal, 295, 308
 Babylonians, 9, 12
 Bacon, R. F., 385, 388
 Bacteria, in coal formation, 347
 in gas formation, 402
 in iron formation, 68
 in nitrogen fixation, 563, 564
 in oil formation, 396, 398
 in sulfur formation, 537
 Badarian culture, 7, 8
 Baddeleyite, 334, 628
 Bain, H. F., 571
 Baker, C. L., 400
 Baku oil field, Russia, 447
 Ball, S. H., 103, 613
 Ball clay, 471
 Banded vein, 54
 Banka, East Indies, tin deposits, 291
 Barite, 577
 domestic deposits, 580
 mode of occurrence, 50, 52, 150, 201,
 268, 269, 318, 345, 538, 578
 origin, 579
 physical properties, 578
 production, 583
 selected readings, 583
 uses, 527, 581, 622
 Barium pigments, 525, 582
 Barre, Vt., granite quarries, 493
 Basalt, 8, 492, 567
 Bastin, E. S., 400, 538
 Batholith, 42
 Battery plates, 308, 315
 Bauer, C. Max, 425
 Baumé scale, 387
 Baux, France, bauxite, 298
 Bauxite, domestic deposits, 299
 foreign deposits, 301
 mode of occurrence, 298
 origin, 65, 298
 physical properties, 297
 production, 304
 selected readings, 305
 uses, 301, 626
 Bawdwin lead-zinc-silver mines, Burma,
 228
 Bayley, W. S., 105
 Beach placers, 258, 324, 334
 Becker, G. F., 393
 Becking, L. B., 396
 Bedded replacement vein, 38
 Bedford, Ind., limestone, 494
 Beehive oven, 377
 Belgian Congo, cobalt, 123
 copper, 185
 uraninite, 332
 Belgium, abrasives, 595
 coal, 371
 lead, 228
 limonite, 110
 zinc, 228
 Bementite, 125
 Bendigo gold district, Australia, 277
 Bentonite, 599
 domestic deposits, 599
 mode of occurrence, 599
 origin, 599
 physical properties, 599
 production, 600
 selected readings, 600
 uses, 600, 622
 Benzene, 381, 383, 386
 Benzol, 381
 Berea sandstone, 501, 596
 Berg, G., 24, 25, 238, 289
 Berthelot, P., 392, 393
 Beryl, 46, 606
 Beryllium, 27, 187
 Bessemer method of steel making, his-
 tory, 86
 process described, 91
 Billiton, East Indies, tin deposits, 291
 Bingham Canon, Utah, copper district,
 167
 lead district, 210
 silver district, 265
 zinc, 216

- Biochemical theory, of coal formation, 347
 of oil formation, 398
 Biotite, 606, 617
 Birmingham, Ala., coal, 99
 iron, 99
 Bisbee, Ariz., copper district, 165
 Bismuth, domestic deposits, 311
 foreign deposits, 311
 mode of occurrence, 50, 311
 ore minerals, 311
 origin, 311
 production, 312
 selected readings, 312
 uses, 312
 Bismuthinite, 311
 Bittern, 552, 576
 Bitumens, 528
 Bituminous coal, 342, 344, 362, 363, 364, 371
 Bituminous rocks, 528
 Black-band ore, 89
 Black diamonds, 597
 Black Hills, S. D., gold district, 247
 limonite, 108
 mica, 619, 621
 spodumene, 590
 tantalum, 329
 tin, 291
 tungsten, 139
 Black sands, 246
 Blanc fixe, 582, 622
 Blast furnace, 90
 Bloodstone, 624
 Blue asbestos, 532
 Blue ground, 612
 Blue powder, 232
 Blue stone, 500
 Bog-iron ores, 107
 Bohemia, cobalt, 123
 garnet, 610
 Bolivia, antimony, 307
 bismuth, 311
 silver, 277
 tin, 277, 291
 Bonanza, 52, 267, 276
 Borax, 567
 Borneo, oil, 451
 Bornite, 148, 160, 178, 181
 Boron, 26, 35
 Bort, 597
 Bradford oil pool, Pa., 439
 Branegan, J. A., 339
 Branson, E. B., 515, 553
 Brass, 231, 294
 Brazil, abrasives, 597
 amethyst, 610
 baddeleyite, 334, 628
 diamonds, 610
 gold, 278
 hematite, 110
 manganese, 128
 monazite, 592
 titanium, 137
 topaz, 610
 zircon, 334, 628
 Brea, 418
 Breckenridge, Colo., bismuth, 311
 zinc-lead district, 221
 Brick clay, 470
 Britannia metal, 294, 309
 British Columbia, cadmium, 314
 copper, 185
 lead, 225
 zinc, 225
 British Guiana, bauxite, 301
 diamonds, 610
 Brochantite, 185
 Broken Hill, New South Wales, lead-zinc district, 225
 Bromine, method of obtaining from brines, 576
 production, 577
 selected readings, 577
 uses, 577
 Bronze, 10, 294, 295
 Bronze age, 10
 Brooks, B. T., 388, 394
 Brooks, T. B., 95
 Brown coal, 340, 371
 Brown (iron) ore, 87, 107
 Brown spar, 584
 Brownstone, 488, 501
 Brusa, Asia Minor, chromite, 120
 sepiolite, 629
 Buckley, E. R., 207
 Buhrstones, 595
 Building sand, 506
 Building stone (*see* Stone).
 Buried placers, 247, 248, 253, 254
 Burley clay, 600
 Burma, gold, 279
 jade, 610
 lead, 228

Burma, oil, 449
 rubies, 610
 sapphire, 610
 silver, 228, 279
 spinel, 610
 tin, 291
 tungsten, 139
 zinc, 228

Burnt umber, 527

Butane, 388, 389

Butler, B. S., 164

Butte, Mont., arsenic, 310
 bismuth, 311
 cadmium, 314
 copper district, 158
 manganese, 127
 tellurium, 330
 zinc district, 160, 216

By-products of coke making, 378, 380

Bytownite, 605

C

Caddo oil pool, La., 440

Cadmium, domestic deposits, 313
 foreign deposits, 314
 mode of occurrence, 313
 ore minerals, 313
 origin, 313
 production, 316
 selected readings, 316
 treatment of ores, 313, 314
 uses, 187, 314

Cadmium yellow, 315, 526

Cairngorm, 624

Calamine (*see* Hemimorphite).

Calaverite, 239, 255, 330

Calcareous tufa, 494

Calcite, 8, 44, 50, 52, 149, 201, 269, 318, 345, 493, 538, 622

Calcium, distribution, 21
 precipitation in sea water, 67

Calcium carbonate, 67

Calcium chloride, 576
 method of obtaining from brines, 576
 production, 577
 selected readings, 577
 uses, 577

Calcium cyanamide, 563

Calcium-molybdenum, 116, 144

Calcium sulfate, 67, 69, 622

California, abrasives, 596

California, andalusite, 625
 antimony, 307
 asphalt, 528
 barite, 581
 basalt, 493
 bentonite, 599
 borates, 567
 calcium and magnesium chlorides, 576
 chromite, 117, 626
 coal, 368
 columbite, 329
 copper, 178, 180, 182
 diatomaceous earth, 597, 604
 dumortierite, 627
 engine sand, 511
 feldspar, 606
 fire clay, 471
 gold, 249
 granite, 493
 ground sand, 512
 gypsum, 516
 kunzite, 612
 lapis lazuli, 610
 lithium, 590
 magnesite, 585
 magnetite, 105
 mercury, 318
 oil and gas, 441-444
 onyx marble, 500
 potash, 562
 pyrite, 543
 salt, 546
 sandstone, 501
 silver, 282
 sodium carbonate, 569
 sodium sulfate, 569
 strontium, 591
 sulfur, 540
 talc, 630
 titanium, 137
 tourmaline, 612
 tungsten, 139

California oil and gas field, 441-444

Calomel, 318, 321

Camp, H. W., 454, 455

Campbell, M. R., 369, 376

Canada (*see* individual provinces).

Cannel coal, 347, 348

Cap rock, 408

Capillary openings, 60, 403

Carboloy, 141

Carbonado, 597

- Carbonation, 62
- Carbon black, 456, 526, 622
- Carbon dioxide, 26, 35, 59, 390
- Carbon monoxide, 26, 35
- Carbonic acid, as a solvent, 72
- Carbonite, 343
- Carborundum, 597, 627
- Carnallite, 562
- Carnelian, 8, 624
- Carnotite, 142, 331, 332
- Carrara, Italy, marble quarries, 497
- Carthage, Mo., limestone, 494
- Cassiterite, 10, 48, 278, 290, 291, 293
- Cast iron, 91
- Cat Creek oil pool, Mont., 445
- Cats-eye, 624
- Celestite, 538, 591, 622
- Cement, 477
 - definition, 479
 - domestic cement plants, 483
 - history, 477
 - kinds, 479
 - manufacture of, 301, 479
 - materials of, 479
 - selected readings, 486
 - uses, 483
- Central copper district, N. M., 175
- Cerargyrite, 74, 240, 259, 262, 266, 277, 278
- Cerium, 591, 592
- Cerro de Pasco, Peru, silver district, 277
- Cerussite, 66, 75, 199, 219
- Ceylon, amethyst, 610
 - graphite, 615
 - monazite, 592
 - sapphire, 610
 - spinel, 610
 - ruby, 610
 - zircon, 610
- Chalcedony, 8, 52, 274, 318, 624
- Chalcocite, 76, 148, 160, 165, 168, 170, 172, 173, 174, 176, 177, 179, 181, 182, 185
- Chalcopyrite, 33, 44, 48, 50, 52, 76, 149, 160, 165, 167, 170, 172, 173, 178, 179, 181, 182, 183, 219, 269, 575
- Chaldeans, 7
- Chalk, 67, 494, 622
- Chamberlin, T. C., 223, 355
- Chemical changes in coal formation, 347
- Chemical origin of oil, 392
- Chemical sediments, chart of, 66
 - deposits of relatively insoluble minerals, 67
 - deposits of very soluble salts, 69
- Chemical weathering, 59
- Chert, 68, 94, 201, 595, 624
- Chile, coal, 372
 - copper, 185
 - lapis lazuli, 610
 - nitrates, 564
 - silver, 277
- Chile niter, 565
- China, antimony, 307
 - coal, 371
 - jade, 610
 - tin, 291
 - tungsten, 139
- China clay, 471
- Chlorides, 35
- Chlorine, 35
- Chosen, graphite, 615
- Chrome green, 526
- Chrome iron, 121
- Chrome red, 526
- Chrome yellow, 526
- Chromite, 26, 33, 34, 117, 626
- Chromium, domestic deposits, 117
 - foreign deposits, 118
 - mode of occurrence, 65, 117
 - ore minerals, 117
 - production, 122
 - uses, 120, 187, 626
- Chromium oxide, 65
- Chrysoberyl, 609
- Chrysocolla, 75, 148, 178
- Chrysoprase, 624
- Chrysotile, 531
- Cinnabar, 52, 318, 321
- Citrine, 624
- Clapp, F. G., 418
- Clarke, F. W., 19, 22, 23, 24, 25, 67, 70, 87, 147, 238, 289, 297, 306, 309, 323, 347, 388, 553, 579
- Classification of mineral deposits, 31, 32
- Clastic dike, 356
- Clastic sedimentary rocks, 64
- Clay, 466
 - commercial varieties, 470
 - composition, 468
 - definition, 467
 - distribution in United States, 470
 - history, 7, 467

- Clay, kinds, 469
 - mode of occurrence, 64, 468
 - origin, 468
 - physical properties, 467
 - selected readings, 476
 - uses, 7, 472, 622
- Clay ironstone, 89
- Clay products, manufacture, 474
 - production, 475
- Clay slip, 355
- Clinton hematite ores, 99
- Coal, composition, 343
 - domestic coal fields, 360, 369
 - foreign coal fields, 369
 - geological distribution, 357
 - history, 339
 - impurities, 345
 - kinds, 340
 - mining, 364
 - mode of occurrence, 352
 - origin, 70, 345-351
 - production, 375
 - rate of accumulation, 352
 - reserves, 368
 - selected readings, 382
 - structural features, 355
 - thickness of beds, 353
 - uses, 372, 622
- Coal blossom, 353
- Coal tar, 380
- Coalingua oil pool, Calif., 443
- Cobalt, 122
 - deposits, 123, 276
 - mode of occurrence, 123
 - ore minerals, 123, 276
 - production, 124
 - uses, 124, 187
- Cobalt, Ont., silver (cobalt, nickel) district, 123, 275, 310
- Cobalt blue, 124, 526
- Cobaltite, 123
- Coeur d'Alene, Idaho, lead district, 209
- Coke (*see* Artificial coke).
- Colemanite, 567
- Collins, W. H., 95
- Colloform banding, 54, 55
- Colloidal silica, 62, 67
- Colombia, asphalt, 528
 - coal, 372
 - emeralds, 610
 - oil, 452
 - platinum, 324
- Colombia, silver, 277
- Colorado, bismuth, 311
 - coal, 363
 - columbite, 329
 - feldspar, 606
 - fire clay, 471
 - fluorite, 573
 - fullers' earth, 608
 - gold, 254, 268, 270
 - gypsum, 516
 - lead, 210, 217
 - limonite, 108
 - manganese, 127
 - marble, 497
 - mica, 621
 - molybdenum, 130
 - monazite, 592
 - oil and gas, 444
 - radium, 332
 - silver, 268, 270
 - tungsten, 138
 - uranium, 332
 - vanadium, 142
 - zinc, 217
- Columbite, 329
- Comb structure, 38
- Comstock Lode gold-silver district, Nev., 267
- Concrete, 479, 485
- Congo, diamonds, 610, 612
- Connate water, 428, 554
- Connecticut, feldspar, 606
 - mica, 621
- Connellsville, Pa., coal, 362
- Connolly, J. P., 249
- Contact-metamorphic deposits, defined, 41
 - examples of, 45, 105
 - metals, 44
 - minerals, 44
 - origin, 45
 - shape, 45
 - size, 45
 - texture, 44
- Coolgardie goldfields, Australia, 277
- Copper, domestic copper districts, 157
 - foreign copper districts, 183
 - gangue minerals, 149
 - history, 8, 145
 - impurities, 151
 - mode of occurrence, 27, 44, 48, 50, 155
 - ore minerals, 148, 149

- Copper, origin, 161, 164, 167, 169, 171,
172, 173, 174, 176, 177, 178, 180,
181, 183
physical properties, 148
production, 158, 188
secondary enrichment, 76, 149
selected readings, 192
treatment of ores, 151
uses, 8, 186
- Copper age, 8
- Copper alloys, 187, 188
- Copper River, Alaska, copper district,
182
- Coquina, 494
- Cornwall, England, arsenic, 310
china clay, 471
tin, 10, 293
uraninite, 332
- Cornwall, Pa., magnetite deposits, 107
- Corundum, 26, 33, 34, 597
- Covellite, 76, 148, 160, 176, 185
- Cox, G. H., 223
- Cripple Creek, Colo., gold district, 254
tellurium, 330
- Crocidolite, 532
- Crooked holes, 427
- Crust of earth, composition, 22
gabbroid layer, 20
granitic layer, 20
- Cryolite, 574
distribution of production, 575
Greenland deposit, 575
mode of occurrence, 575
physical properties, 574
selected readings, 575
uses, 575
- Cuba, chromite, 120
hematite, 110
- Cupola, 42
- Cuprite, 75, 148, 165, 176
- Cushing oil pool, Okla., 440
- Cut out, 356
- Cuyuna iron range, Minn., 94
- Cyprians, 9
- Czechoslovakia, graphite, 615
magnesite, 586
mercury, 321
oil, 452
sepiolite, 629
uraninite, 332
zinc, 228
- D
- Daly, R. A., 19, 25
- Darton, N. H., 517
- Daubreé, G., 393
- Davison, E. H., 43, 293
- Day, D. T., 392, 394, 395
- Death Valley, Calif., colemanite, 567
- Deep-seated vein zone deposits, examples
of, 49
metals, 48
minerals, 48
mode of occurrence, 49
origin, 49
shape, 48
size, 48
- De Launay, Louis, 279
- Delaware, china clay, 471
- Denmark, abrasives, 595
- Depth of oil and gas wells, 422
- Depth to which water penetrates, 61
- Descloizite, 142
- Detrital ore deposits (*see* Residual ore
deposits).
- Diabase, 492
- Diamond, 492
African deposits, 34, 612
occurrence, 33
origin, 610
price, 612
production, 612, 613
- Diamond dust, 597
- Diaspore clay, 600
composition, 600
domestic deposits, 472, 602
mode of occurrence, 601
physical properties, 601
production, 602
selected readings, 602
uses, 602, 627
- Diatomaceous earth, 602
composition, 603
domestic deposits, 603
mode of occurrence, 603
origin, 69, 603
physical properties, 603
production, 604
selected readings, 605
uses, 597, 604, 622
- Diatoms, in oil formation, 394, 603
- Diopside, 44
- Diorite, 492

Disseminated deposits, 36, 156, 205, 275
 Dolomite, 587
 composition, 587
 geologic distribution, 589
 occurrence, 50, 52, 201, 269, 494, 588
 origin, 68
 physical properties, 588
 selected readings, 589
 uses, 589, 622, 627
 Dolomite, as a reservoir rock, 407
 Dorsey, G. E., 396
 Drake, E. L., 385, 423
 Dry wells, 425
 Ducktown, Tenn., copper district, 179
 Dull coal, 342, 348
 Dumortierite, 627
 Dunite, 30, 32, 324, 626
 Durain, 342
 Duraluminum, 303
 Dutch East Indies, oil, 449
 Dutch Guiana, bauxite, 301
 Dynamochemical changes in coal forma-
 tion, 349

E

Earth, composition, 18
 composition by elements, 22
 physical state, 17
 vertical distribution of elements, 21
 zonal arrangement of constituents, 19
 Earth materials used by ancient man,
 6-13
 Earthenware clay, 470
 Eastern Interior coal field, 363
 Economic geology, defined, 3
 Ecuador, oil, 451
 Egypt, oil, 450
 Egyptians, 7, 8, 9, 10, 11, 12, 13
 El Oro gold mine, Mexico, 276
 Eldorado oil pool, Kan., 440
 Elk Hills oil pool, Calif., 443
 Ely, Nev., copper district, 174
 Emerald, 46, 610, 611, 613
 Emery, 79, 597
 Emmons, S. F., 219
 Emmons, W. H., 43, 46, 48, 55
 Enargite, 149, 160, 262, 309
 End products, of chemical weathering, 63
 of magma splitting, 30
 Engine sand, 511
 England, arsenic, 310

England, barite, 579
 china clay, 471
 coal, 371
 fluorite, 574
 oil, 452
 siderite, 110
 tin, 293
 uraninite, 332
 Engler, C., 392, 394
 Epidote, 44
 Epigenetic ore deposits, 34
 causes of deposition, 38
 character of mother liquors forming
 them, 34
 defined, 31
 kinds, 40
 where deposition occurred, 36
 Erthyrite, 123
 Estuarian clays, 470
 Ethane, 388, 389
 Eureka, Nev., gold-silver district, 267
 Eureka-Silverton zinc-lead district, Colo.,
 220
 Eutectics, 48

F

Fat clays, 467
 Faults in coal, 356
 Feldspar, alteration, 59
 domestic deposits, 606
 minerals, 605
 mode of occurrence, 46, 48, 64, 150,
 492, 606
 physical properties, 605
 production, 607
 selected readings, 607
 uses, 606, 622
 Felsite, 492
 Ferberite, 138
 Ferro-alloys, 116
 Ferrochromium, 116, 121
 Ferromagnesian minerals, 26
 Ferromanganese, 116, 125, 128
 Ferromolybdenum, 116, 131
 Ferrophosphorus, 116, 144, 560
 Ferrosilicon, 116, 144
 Ferrosporic zone of earth, 20
 Ferrotitanium, 116, 137
 Ferrotungsten, 116, 139
 Ferrovanadium, 116, 143
 Ferrozirconium, 116, 335

- Ferruginous chart, 94
 Fertilizers, 555-566
 glauconite, 566
 lime, 566
 nitrogen compounds, 563
 phosphates, 556
 potash, 561
 sulfur, 566
 Fettke, C. R., 507
 Field, John, 396
 Fierro, N. M., magnetite deposits, 105
 Filled-fissure vein, 36
 Filter sand, 511
 Fire clay, 471
 Fire sand (*see* Furnace sand).
 Fissure deposits, 155, 205
 Flagstone, 500
 Flake white, 622
 Flint, 6, 68, 595, 622, 624
 Flint clay, 470
 Flood-plain clays, 470
 Florence oil field, Colo., 408, 444
 Florida, china clay, 471
 diatomaceous earth, 604
 fullers' earth, 608
 monazite, 592
 phosphate rock, 557
 titanium, 137
 zircon, 334, 628
 Fluorides, 35
 Fluorine, 26, 35
 Fluorite, 570
 domestic deposits, 571
 mode of occurrence, 50, 52, 201, 255,
 269, 290, 293, 571, 575
 origin, 571
 physical properties, 570
 production, 574
 selected readings, 575
 uses, 573
 Foot wall, 36
 Foothill Belt copper district, Calif., 182
 Fossil iron ore, 88, 100
 Foundry sand (*see* Molding sand).
 Fragmental products of weathering, 63
 France, abrasives, 595
 bauxite, 301
 coal, 371
 lead, 228
 limonite, 110
 oil, 452
 potash, 562
 pyrite, 543
 zinc, 228
 Franklin, N. J., zinc district, 214
 Franklinite, 125, 200, 215
 French Morocco, bauxite, 301
 Fuller, M. F., 72
 Fullers' earth, 607
 characteristics, 608
 domestic deposits, 608
 production, 609
 selected readings, 609
 use, 608, 622
 Fumarole, 56
 Furnace sand, 511
 Furness, J. W., 294, 295
 Fusian, 348
- G
- Gabbro, 34, 324, 492
 Gabbroid layer of earth's crust, 20
 Galena, 48, 50, 52, 66, 74, 77, 150, 199,
 207, 209, 210, 211, 216, 219, 220, 221,
 222, 223, 262, 264, 265, 268, 269, 270,
 276, 306, 575
 Galicia, oil, 447
 Galvanizing, 231
 Gangue mineral, defined, 50
 Ganister, 501, 627
 Gannett, Henry, 376
 Garber oil pool, Okla., 440
 Garnet, as abrasive, 596
 as gem, 610, 611, 612
 occurrence, 44, 46, 79, 606
 Gas (*see* Natural gas).
 Gash veins, 223
 Gasoline, 383, 386, 390
 Gautier, A., 46
 Gem-stones, 609, 610
 Gems and semiprecious stones, 609
 domestic deposits, 612
 foreign deposits, 612
 origin, 64, 610
 physical properties, 609
 selected readings, 613
 value, 612, 613
 Genthite, 132, 134
 Geophysical methods of studying rock
 structures, 419
 Georgia, anthophyllite, 532
 barite, 580
 bauxite, 300, 626

- Georgia, china clay, 471
columbite, 329
feldspar, 606
fullers' earth, 608
granite, 493
graphite, 614
limonite, 108
manganese, 127
marble, 496
mica, 621
ocher, 527
pyrite, 543
pyrophyllite, 623
serpentine, 500
slate, 503
talc, 630
tantalite, 329
tripoli, 634
Georgian Republic, manganese, 127
German silver, 135, 232
Germany, barite, 579
bauxite, 301
coal, 371
cobalt, 123
copper, 186
gold, 279
graphite, 614
limonite, 110
oil, 449
potash, 562
pyrite, 543
salt, 549
silver, 279
uraninite, 332
zinc, 228
Gilbert, C. G., 457
Gilsonite, 528
Glacial clays, 470
Glance coal, 342, 348
Glass sand, 507
composition, 507
domestic deposits, 509
manufacture of glass, 510
selected readings, 513
Glauber salt, 569
Glauconite, 562, 566
Glenn-Kiefer oil pool, Okla., 440
Globe-Miami copper district, Ariz., 170
Gneiss, 78, 492
Gold and silver, domestic production, 282
Gold and silver, foreign gold and silver districts, 270
gangue minerals, 240
gold districts of United States, 247
gold-silver districts of United States, 266
history, 11, 235
impurities, 242
mode of occurrence, 27, 44, 48, 50, 52, 64, 74, 150, 245, 253
ore minerals, 238
origin, 249, 251, 252, 253, 255, 257, 258, 259, 260, 263, 265, 266, 267, 273, 276
physical properties, 238
placers, 253
secondary enrichment, 247
selected readings, 287
silver districts of United States, 260
tenor of ores, 241, 254
treatment of ores, 242
use, 11, 279
world production, 285
Gold coast, diamonds, 612
manganese, 128
Gold dredge, 242
Gold dust, 246
Gold leaf, manufacture of, 280
Gold tellurides, 269, 275, 277, 330
Goldfield, Nev., gold district, 259
Goldschmidt, V. M., 19, 20
Gondite ores, 127
Gossan, 73, 74, 180
Grabau, A. W., 553
Granite, domestic deposits, 493
physical properties, 492
use, 8, 493
Granitic layer of earth's crust, 20
Graphic granite, 48
Graphite, 613
domestic deposits, 614
foreign deposits, 615
mode of occurrence, 79, 614
origin, 614
physical properties, 613
production, 616
selected readings, 616
uses, 526, 527, 615, 622, 627
Grass Valley-Nevada City gold district, Calif., 252
Gravel (*see* Sand and gravel).
Great Britain (*see* individual countries).

- Greece, chromite, 120
 emery, 597
 magnesite, 586
 nickel, 135
 sepiolite, 629
 Greenalite, 94
 Greenland, cryolite, 575
 Greenockite, 313
 Grindstones, 596
 Griqualand, Union of South Africa,
 asbestos (crocidolite), 532
 Ground sand, 512
 uses, 512
 Ground talc, 631
 Ground water, 61, 62
 Grout, F. F., 95, 97
 Gruner, J. W., 95, 97
 Guanajuato silver district, Mexico, 276
 Guatemala, chromite, 120
 Guignet green, 568
 Gulf Coast, lignite field, 364
 oil and gas field, 446
 Gusher, 431
 Gypsite, 514, 518
 Gypsum, 513
 composition, 514
 domestic deposits, 516
 geologic distribution, 516
 history, 513
 mode of occurrence, 345, 515, 538, 549
 origin, 69, 515
 physical properties, 514
 preparation for use, 517
 selected readings, 519
 uses, 518, 555, 566, 622
 varieties, 515
- H
- Halite (*see* Salt).
 Hamor, W. A., 385, 388
 Hanging wall, 36
 Harris, G. D., 414
 Hartville, Wyo., hematite deposits, 102
 Hashimoto, T., 396
 Hausmanite, 125
 Haworth, E., 553
 Hayes, C. W., 299
 Heliotrope, 624
 Helium, 389
 Hematite, 26, 33, 87, 93, 99, 102, 103, 110
 Hematite pigments, 526
 Hemimorphite, 75, 199, 212, 219, 223
 Hess, F. L., 138, 140, 328
 Hidalgo silver district, Mexico, 276
 Hildreth, S. P., 384
 Hilt, Carl, 349
 Höfer, A., 392, 394
 Holland (*see* Netherlands).
 Homestake mine, S. D., gold, 247
 wolframite, 139
 Hones, 596
 Horn silver, 240, 266
 Hornblende, 26, 46
 Hornstone, 624
 Horse, 38
 Horseback, 356
 Hot springs, 57, 318, 573
 Hough, Walter, 339
 Howard, W. V., 408
 Hubnerite, 138
 Hunan province, China, antimony, 307
 tungsten, 139
 Hungary, bauxite, 301
 opal, 610
 Hunt, T. S., 402
 Huntington Beach oil pool, Calif.,
 443
 Hydration, 62
 Hydrochloric acid, 35
 Hydrogen, 34
 Hydrogen sulfide, 26, 34
 Hydrolysis, 62
 Hydrothermal alterations, 35
- I
- Idaho, antimony, 307
 barite, 581
 basalt, 493
 bentonite, 600
 cobalt, 123
 lead, 209
 monazite, 592
 phosphate rock, 559
 salt, 546
 silver, 282
 zinc, 209
 Igneous rocks, types, 30, 31, 32
 Illinois, coal, 363
 filter sand, 511
 fire clay, 471
 fluorite, 571
 fullers' earth, 608

- Illinois, glass sand, 509
 lead, 222
 molding sand, 507
 oil and gas, 444
 pyrite, 543
 tripoli, 596, 633
 zinc, 222
- Illinois and southwest-Indiana oil and gas field, 444
- Ilmenite, 26, 33, 34, 48, 137
- Importance of earth materials, 13
- India, amethyst, 610
 bauxite, 301
 chromite, 120
 coal, 371
 gold, 279
 iron, 110
 jade, 610
 lead, 228
 magnesite, 586
 manganese, 128
 mica, 619
 monazite, 592
 oil, 449
 rubies, 610
 sapphire, 610
 silver, 228
 spinel, 610
 tin, 291
 titanium, 137
 tungsten, 139
 zinc, 228
 zirconium, 334
- Indiana, abrasives, 596
 coal, 363
 engine sand, 511
 fire clay, 471
 limestone, 494
 molding sand, 507
 oil and gas, 444, 445
 pyrite, 543
- Inner core of earth, 19
- Intermediate vein zone deposits, examples, 52
 metals, 50
 minerals, 50
 mode of occurrence, 50
 origin, 51
 shape, 50
 size, 50
 texture, 50
- Iowa, coal, 363
- Iowa, gypsum, 516
- Iraq (or Mesopotamia), oil, 453
- Iridium, 134, 323
- Iron, distribution, 21
 domestic deposits, 92
 foreign deposits, 108
 history, 11, 85
 impurities, 89
 mode of occurrence, 27, 44, 48, 65, 92
 ore minerals, 87
 origin, 68, 95, 102, 103, 104, 105, 107, 108
 production, 111
 selected readings, 115
 treatment of ores, 89
 use, 110, 187
- Iron age, 11
- Iron hat, 73
- Iron-molding sand, 506
- Iron Mountain, Mo., hematite deposits, 103
- Iron oxides, 65, 74, 75, 150, 508, 622
- Iron Springs, Utah, 43, 106
- Irving, J. D., 220
- Isinglass, 617
- Italy, graphite, 615
 lead, 228
 marble, 497
 mercury, 321
 onyx, 497
 pyrite, 543
 sulfur, 537
 travertine, 497
 zinc, 228
- J
- Jade, 610
- Japan, arsenic, 310
 bismuth, 311
 copper, 186
 gold, 279
 oil, 449
 platinum, 325
 pyrite, 543
 sulfur, 537
 zinc, 234
- Jarbridge gold district, Nev., 258
- Jasper, 624
- Jasper-agate, 624
- Jerome, Ariz., copper district, 171
- Jet, 348

Jones, I. W., 349
 Jugoslavia, bauxite, 301
 Julien, A. A., 490
 Julihn, C. E., 145, 185, 192
 Juneau gold district, Alaska, 256

K

Kainite, 562
 Kalgoorlie gold district, Australia, 277
 Kansas, cadmium, 214, 314
 coal, 363
 engine sand, 511
 gypsum, 517
 lead, 211
 oil and gas, 440
 pumicite, 596
 salt, 548
 zinc, 211
 Kaolin, 59, 62, 64, 65, 471
 Katanga, Belgian Congo, cobalt, 123
 copper, 185
 Keene's cement, 519
 Kemp, J. F., 71, 105
 Kentucky, asphaltic rock, 528
 ball clay, 471
 barite, 581
 coal, 362, 363
 fluorite, 571
 oil and gas, 439
 onyx marble, 500
 phosphate rock, 558
 pottery clay, 471
 siderite, 89
 Kernite, 567
 Kerogen, 400
 Kerosene, 383, 387
 Kidney iron ore, 88
 Kimberlite, 612
 Kirkland Lake, Ont. (*see* Porcupine
 and Kirkland Lake gold district,
 Ont.).
 Knopf, A., 251
 Kolar goldfield, India, 279
 Kraemer, G., 394
 Kunz, G. F., 612
 Kunzite, 610, 612

L

Labradorite, 605
 Ladoo, R. B., 137, 590, 621, 631

Lahee, F. H., 427
 Lake clays, 470
 Lake County-Boulder County gold-silver
 district, Colo., 270
 Lake Superior, Mich., copper district,
 146, 162
 hematite deposits, 93
 Land plaster, 518
 Lapis lazuli, 8, 610
 Larsen, E. S., 25
 Laterites, 65, 298
 Laurite, 323
 Lead and zinc, domestic production, 232
 foreign lead and zinc districts, 225
 gangue minerals, 201
 history, 12, 194
 impurities, 202
 lead districts of United States, 205
 mode of occurrence, 27, 44, 48, 50, 52,
 66, 204
 ore minerals, 198
 origin, 207, 209, 213, 215, 219, 221,
 222, 223, 224, 225
 physical properties of minerals, 199
 secondary enrichment, 201
 selected readings, 234
 tenor of ores, 201
 treatment of ores, 202
 types of ores, 201
 use, 12, 187, 228
 world production, 234
 zinc districts, 210
 zinc-lead districts, 217
 Lead pigments, 229, 524
 Lead sulfide, 65
 Leadville, Colo., bismuth, 311
 limonite, 108
 manganese, 127
 zinc and lead district, 217
 Lean clays, 467
 Lehigh Valley, Pa., 3, 479
 Leith, C. K., 95, 97, 553, 556
 Lepidolite, 590
 Lignite, 340, 344, 364, 371
 Lilley, E. R., 405
 Lima (Ohio)-Indiana oil and gas field, 445
 Lime, manufacture, 520
 selected readings, 523
 uses, 523, 566, 622
 Limestone, 493
 domestic deposits, 494
 mode of occurrence, 493

Limestone, origin, 67, 69
 physical properties, 494
 uses, 7, 495, 555, 566, 622
 varieties, 495
 Limestone as a reservoir rock, 407
 Limonite, 88, 107, 110
 Limonite pigments, 526
 Lindgren, W., 43, 52, 71, 172, 173, 553, 619
 Linnaeite, 123, 132, 135
 Lipari, pumice, 596
 Litharge, 229
 Lithium, 590
 mode of occurrence, 27, 47, 590
 ore minerals, 590
 selected readings, 590
 use, 590
 Lithopone, 232, 524, 525, 582, 622
 Lithosporic zone of earth, 19
 Lode, 38, 49, 53, 256, 291
 Lodestone, 88
 Lorraine iron ores, 110
 Loughlin, C. F., 220
 Louisiana, anhydrite, 516
 asphalt, 528
 coal, 364
 oil and gas, 440, 446
 salt, 546, 549
 sulfur, 538
 Lower California, antimony, 307
 Lubricating oils, 383
 Luxembourg, limonite deposits, 110

M

Mabery, C. F., 457
 Madagascar, graphite, 615
 radium, 332
 tourmaline, 610
 uranium, 332
 Magma, composition, 25
 consolidation, 26
 definition, 25
 movement, 25
 order of crystallization, 26
 size, 25
 splitting, 27
 Magmatic segregations, 33
 Magmatic waters, 26, 31, 56, 77
 Magnesia alba, 622
 Magnesite, 584
 composition, 584
 domestic deposits, 585
 foreign deposits, 586
 mode of occurrence, 584
 origin, 68, 585
 physical properties, 584
 production, 587
 selected readings, 589
 uses, 317, 586, 622, 627
 Magnesium, distribution, 21
 origin, 68
 production, 317
 source, 316
 uses, 316
 Magnesium carbonate, 67
 Magnesium chloride, 576
 method of obtaining from brines, 576
 production, 577
 selected readings, 577
 uses, 577
 Magnetite, 26, 33, 34, 44, 48, 88, 103, 105, 110
 Maine, diatomaceous earth, 604
 feldspar, 606
 granite, 493
 lime, 521
 mica, 619, 621
 molybdenum, 131
 slate, 503
 Malachite, 8, 75, 148, 165, 178
 Malay States, tin, 291
 Manchuria, magnesite, 586
 Manganese, 124
 domestic deposits, 127
 foreign deposits, 127
 mode of occurrence, 65, 125
 ore minerals, 124
 origin, 69, 126
 production, 129
 selected readings, 129
 use, 128, 187
 Manganese bronze, 232
 Manganese oxides, 65, 125
 Manganite, 125
 Manganotantalite, 329
 Manning, P. D. V., 568
 Mansfield shale (copper bearing), Germany, 186
 Mansfield, G. R., 557
 Mantle rock, 64
 Manufactured mineral fillers, list of, 622
 Marble, 496
 domestic deposits, 496

- Marble, foreign deposits, 497
 origin, 78
 uses, 497
Marble dust, 622
Marcasite, 52, 201, 223, 273, 318, 345
Marden, J. W., 143
Marine clays, 470
Marquette iron range, Mich., 93
Marsh gas, 388
Maryland, china clay, 471
 chromite, 117, 626
 chrysotile, 533
 coal, 362
 diatomaceous earth, 604
 feldspar, 606
 ground sand, 512
 serpentine, 500
 slate, 503
 tale, 630
Massachusetts, feldspar, 606
 fullers' earth, 608
 granite, 493
 lime, 521
 pyrite, 543
 serpentine, 500
Mat coal, 342, 348
Maynard, J. E., 97, 98, 102
McMillin, H. F., 396
Mead, W. J., 298, 299
Mechanical weathering, 59
Meerschaum (*see* Sepiolite).
Mellor, E. T., 274
Mendeléeff, D., 392, 393
Menominee iron range, Mich., 93
Mercury, domestic deposits, 319
 foreign deposits, 321
 mode of occurrence, 52, 318
 ore minerals, 318
 origin, 318
 production, 322
 selected readings, 322
 tenor of ores, 318
 treatment of ores, 318
 uses, 321
Mesabi iron range, Minn., 94
Metacinnabarite, 318
Metallogenetic epochs, 79
Metamorphic ore deposits, 33
Metamorphic rocks, 33, 78
Metasomatism, 45, 52
Methane, 388
Meteoric water, 39, 56, 59, 60, 61, 65,
 70, 71
Mexico, antimony, 307
 arsenic, 310
 asphalt, 528
 copper, 185
 gold, 276
 graphite, 615
 lead, 225
 mercury, 321
 oil, 449
 opal, 610
 silver, 276
 sulfur, 537
 vadium, 143
 zinc, 225
Mica, 617
 domestic deposits, 619
 foreign deposits, 619
 mode of occurrence, 46, 48, 64, 79, 617
 origin, 619
 physical properties, 617
 production, 620
 selected readings, 621
 treatment, 620
 uses, 620, 622
 varieties, 617
Michigan, abrasives, 596
 anhydrite, 516
 calcium and magnesium chloride and
 bromine, 576
 coal, 363
 copper, 162
 graphite, 614
 gypsum, 516
 hematite, 93
 lime, 521
 manganese, 127
 molding sand, 507
 oil and gas, 446
 salt, 546, 550
 strontium, 591
Michigan oil and gas field, 446
Microcline, 605
Mid-Continent oil and gas field, 440
Midway-Sunset oil pool, Calif., 443
Migration of petroleum, 403-406
Milky quartz, 624
Millerite, 132
Mills, R. Van A., 424
Millstones, 595
Mine la Motte, Mo., 123, 206

- Mineral, definition, 15
Mineral charcoal, 348
Mineral deposit, definition, 15
Mineral fillers, 621
 manufactured, 622
 natural, 622
 selected readings, 622
 uses, 622
Mineral paints, 523
 manufactured pigments, 524
 natural pigments, 526
 selected readings, 527
Mineralizers, 34, 35
Minettes, 110
Mineville, N. Y., magnetite deposits, 104
Minnesota, abrasives, 595
 granite, 493
 hematite, 93
 manganiferous iron, 94, 127
 mica, 619
 peat, 364
 titaniferous magnetite, 107
Mirabilite, 569
Mississippi, tripoli, 634
Missouri, abrasives, 596
 ball clay, 471
 barite, 580
 cadmium, 214, 314
 coal, 363
 cobalt, 123
 diaspore, 472, 602
 fire clay, 471
 glass sand, 509
 granite, 493
 ground sand, 512
 hematite (specularite), 103
 lead, 206, 211
 lime, 521
 lime-stone, 494
 marble, 497
 nickel, 135
 tripoli, 596, 633
 tungsten, 139
 zinc, 211
Mocha stone, 624
Mode of occurrence, defined, 3
Molding sand, 506
Molybdenite, 44, 48, 130, 290
Molybdenum, domestic deposits, 130
 foreign deposits, 131
 mode of occurrence, 48, 50, 130
 ore minerals, 130
Molybdenum, origin, 130
 production, 132
 selected readings, 132
 use, 131
Molybdate, 130
Monazite and thorium, 591
 composition, 591
 domestic deposits, 592
 foreign deposits, 592
 physical properties, 592
 selected readings, 592
 use, 592
Monel metal, 135, 317
Montana, arsenic, 310
 barite, 581
 bentonite, 600
 bismuth, 311
 cadmium, 314
 chromite, 117
 chrysotile, 533
 coal, 363
 copper, 158
 gold, 282
 graphite, 614
 gypsum, 516
 lead, 210
 limonite, 108
 manganese, 127
 oil and gas, 445
 phosphate rock, 559
 sapphires, 612
 silver, 282
 zinc, 216
Monte Amiata, Italy, mercury district, 321
Moore, E. S., 97, 98, 102
Morenci-Metcalf copper district, Ariz., 172
Morro Velho gold mine, Brazil, 278
Moss agate, 624
Mother liquors, 31
Mother Lode Belt, Calif., gold district, 249
Mother-of-coal, 348
Mount Isa, Queensland, lead-zinc district, 225
Mount Morgan, Queensland, gold mine, 277
Munn, M. J., 404, 405
Muscovite, 46, 290, 501, 617, 619, 620

N

- Naptha, 383, 386
- Naphthalene, 382
- Native arsenic, 309
- Native bismuth, 311
- Native copper, 75, 148, 156, 163, 165, 176
- Native gold, 50, 52, 75, 238, 248, 250, 252, 253, 257, 258, 259, 260, 267, 269, 273, 275, 276, 277, 279
- Native mercury, 318, 322
- Native silver, 75, 239, 262, 268, 276, 277, 278
- Native tellurium, 330
- Natural abrasives, 595
- Natural brines, 549, 576
- Natural cement, 482
- Natural coke, 343
- Natural gas, 388 (*see also* Petroleum and natural gas).
- Natural mineral fillers, list of, 622
- Natural sodium compounds, 566
 - borates, 69, 567
 - carbonates, 69, 568
 - nitrate, 69, 564
 - origin, 69
 - selected readings, 569
 - sulfates, 69, 569
 - uses, 567, 569
- Nebraska, abrasives, 596
 - diatomaceous earth, 604
 - potash, 562
 - sodium carbonate, 569
- Netherlands, zinc, 234
- Nevada, abrasives, 595, 597
 - antimony, 307
 - barite, 581
 - bismuth, 311
 - borates, 567
 - china clay, 471
 - cobalt, 124
 - copper, 174
 - diatomaceous earth, 604
 - fluorite, 573
 - fullers' earth, 608
 - gold, 258, 259, 267
 - graphite, 614
 - ground sand, 512
 - gypsum, 516
 - lead, 210
 - limonite, 108
 - magnesite, 586
 - Nevada, mercury, 320
 - mica, 621
 - opal, 612
 - platinum, 324
 - salt, 546, 548
 - silver, 267
 - sodium carbonate, 569
 - sulfur, 540
 - thenardite, 569
 - tin, 291
 - tripoli, 634
 - tungsten, 139
 - vanadium, 143
 - New Almaden mercury mine, Calif., 320
 - New Caledonia, chromite, 34, 120
 - nickel, 132, 134
 - New Hampshire, abrasives, 596, 597
 - diatomaceous earth, 604
 - feldspar, 606
 - fluorite, 573
 - granite, 493
 - mica, 621
 - New Idria mercury mine, Calif., 320
 - New Jersey, ball clay, 471
 - diatomaceous earth, 604
 - filter sand, 511
 - fire clay, 471
 - glass sand, 509
 - glauconite, 566
 - ground sand, 512
 - magnetite, 104, 105
 - molding sand, 507
 - pottery clay, 471
 - serpentine, 500
 - talc, 630
 - zinc, 214
 - New Mexico, abrasives, 596
 - anhydrite, 516
 - bentonite, 600
 - bismuth, 311
 - coal, 363
 - columbite, 329
 - copper, 175
 - diatomaceous earth, 604
 - feldspar, 606
 - fluorite, 573
 - gypsum, 517
 - lead, 224
 - limonite, 108
 - magnetite, 105
 - manganese, 127

- New Mexico, mica, 621
molybdenum, 131
oil and gas, 445
potash, 562
salt, 546, 548
sepiolite, 629
silver, 282
thenardite, 569
turquoise, 612
vanadium, 143
zinc, 224
- New South Wales, lead, 225
molybdenum, 131
opal, 610
silver, 225
tin, 293
zinc, 225
- New York, abrasives, 596, 597
diatomaceous earth, 604
feldspar, 606
graphite, 615
ground sand, 512
gypsum, 516
hematite, 99
ilmenite, 34
magnetite, 104
molding sand, 507
oil and gas, 439
pyrite, 543
salt, 548
sandstone, 501
slate, 503
strontium, 591
talc, 630
titaniferous magnetite, 107
- New Zealand, coal, 371
- Newfoundland, hematite, 110
- Newland, D. H., 105
- Nicolite, 132
- Nichrome, 121, 135
- Nickel, 132
deposits, 134
distribution, 21
mode of occurrence, 132
ore minerals, 132
origin, 65, 133
production, 136
selected readings, 136
uses, 135, 187
- Nickel silicates, 65
- Nigeria, coal, 372
tin, 291
- Nitrogen, 34, 388, 389
- Nitrogen compounds, 563
nitrate deposits, 564
nitrogen fixation, 563
occurrence of nitrogen in nature, 563
origin of nitrates, 565
production, 565
selected readings, 565
- Nome, Alaska, gold district, 258
- North Carolina, abrasives, 596, 597
barite, 581
china clay, 471
chromite, 117
coal, 368
columbite, 329
corundum, 34, 597
feldspar, 606
ground sand, 512
magnetite, 104
mica, 621
monazite, 592
pyrophyllite, 623
talc, 631
tin, 291
- North Dakota, coal, 363
- Northern interior coal field, 363
- Northern Territory, Australia, tin deposits, 293
- Norway, ilmenite, 34
molybdenum, 131
pyrite, 543
titanium, 137
- Novaculite, 596
- Nuggets of gold, 246
- O
- Ocher pigments, 7, 527, 622
- Ochsenius, C., 552
- Ohio, abrasives, 596
calcium and magnesium chlorides and bromine, 576
coal, 362
engine sand, 511
fire clay, 471
ground sand, 512
gypsum, 516
lime, 521
molding sand, 507
oil and gas, 439, 445
pyrite, 543
salt, 550

- Ohio, sandstone, 501
 - siderite, 89
 - strontium, 591
- Oil (*see* Petroleum).
- Oilstones, 596
- Oklahoma, cadmium, 214, 314
 - coal, 363
 - granite, 493
 - gypsum, 516
 - lead, 211
 - oil and gas, 440
 - salt, 546
 - tripoli, 633
 - zinc, 211
- Oligoclase, 605
- Olivine, 19, 20, 21, 26, 30, 133, 324, 532
- Ontario, cobalt, 123
 - corundum, 34
 - gold, 274
 - hematite, 93
 - iridium, 134
 - lead, 228
 - mica, 619
 - nickel, 133, 134
 - oil, 447
 - osmium, 134
 - palladium, 134
 - platinum, 134
 - ruthenium, 134
 - silver, 134, 275
 - zinc, 228
- Onyx, 494, 500, 524
- Oolitic iron ore, 88, 100, 110
- Oolitic limestone, 494
- Opal, 52, 318, 610, 611, 612
- Open-hearth method of steel making,
 - history, 86
 - process, 91
- Openings in rocks, 60
- Ophicalcite, 499
- Ore, defined, 15
- Ore deposit, defined, 15
- Ore shoots, 53
- Oregon, abrasives, 597
 - basalt, 493
 - borates, 567
 - chromite, 117
 - chrysotile, 533
 - diatomaceous earth, 604
 - mercury, 320
 - monazite, 592
 - nickel, 134
 - Oregon, platinum, 324
 - Organic origin of oil, 394
 - Organic sediments, calcareous, 69
 - carbonaceous, 70, 339, 383
 - chart of, 66
 - siliceous, 69
 - Oriskany sandstone, 509
 - Orpiment, 309
 - Orthoclase, 26, 62, 605
 - Osmiridium, 323
 - Osmium, 134, 323
 - Otavite, 313
 - Oxidation, 62, 73
 - Oxidized ores, 74, 149, 165, 173, 176, 178
 - Oxygen, 21, 34, 59
 - Ozokerite, 528

P

 - Pacific Coast coal field, 364
 - Pack, R. W., 443
 - Palladium, 134, 323
 - Palmer, L. A., 584
 - Panning gold, 244
 - Paper clay, 470
 - Paraffin, 383, 387, 528
 - Paris green, 310
 - Park City, Utah, lead district, 210
 - silver district, 263
 - zinc, 216
 - Parker, E. W., 375
 - Parting in coal, 355
 - Patronite, 142
 - Paving sand, 506
 - Pearl filler, 622
 - Pearl hardening, 622
 - Pearls, 613
 - Peat, 340
 - Peat bogs, 345
 - Peat fields of United States, 364
 - Pebbles for grinding, 595
 - Pegmatites, minerals, 46
 - mode of occurrence, 47, 575
 - origin, 47, 606
 - shape, 47
 - size, 47
 - size of crystals, 46
 - Pehrson, E. W., 195
 - Pennsylvania, abrasives, 596
 - china clay, 471
 - chromite, 117
 - coal, 362

- Pennsylvania, engine sand, 511
feldspar, 606
fire clay, 471
glass sand, 509
ground sand, 512
gypsum, 516
lime, 521
magnetite, 105
molding sand, 507
ocher, 527
oil and gas, 439
salt, 546
sandstone, 501
serpentine, 500
slate, 502
talc, 630
- Penokee-Gogebic iron range, Mich.-
Wis., 93
- Penrose, R. A. F., 565
- Pentlandite, 33, 132, 134, 324
- Peridot, 610, 612
- Peridotite, 30, 32, 117, 133, 611, 630
- Peridotitic zone of earth, 20
- Persia, amethyst, 610
oil, 450
turquoise, 610
- Persistent minerals, 48, 50, 52, 58
- Peru, coal, 372
copper, 185
oil, 449
silver, 277
vanadium, 142, 143
- Petrie, Sir Flinders, 7, 9, 10, 486
- Petroleum and natural gas, 383
accumulation, 406-418
composition, 385
domestic oil fields, 437
foreign oil fields, 447
geological distribution, 435
history, 383
migration, 403-406
origin, 70, 392-402
physical properties, 386
production, 457, 458
selected readings, 459
subsurface studies, 419
uses, 453
- Philippine Islands, gold, 282
- Phlogopite, 617-620
- Phoenicians, 12
- Phosphate rock, 556
domestic deposits, 557
Phosphate rock, mode of occurrence, 556
origin, 68, 557
selected readings, 560
uses, 560
- Phosphates, 67
- Phosphorus, 26, 35
- Phyllite, 501
- Pig iron, 90
- Pioneer, Ariz., copper district, 181
- Pipe clay, 470
- Pishel, Max A., 379
- Pitchblende, 331, 332
- Pittsburg coal bed, 354
- Placer gold deposits, Calif., 253
- Placers, 64, 246, 253, 258, 274, 291, 324,
334
- Plagioclase, 26
- Plasma, 624
- Plaster, 521
- Plaster of Paris, 518
- Platiniridium, 323
- Platinum and related metals, domestic
deposits, 324
foreign deposits, 134, 324
mode of occurrence, 33, 34, 64, 323
ore minerals, 323
origin, 324
production, 327
selected readings, 327
use, 325
- Plumas County, Calif., copper district,
180
- Pogue, J. E., 457
- Poland, bauxite, 301
cadmium, 314
coal, 371
lead, 228
oil, 447
salt, 544
zinc, 228
- Polianite, 125
- Polybasite, 268, 276
- Polyhalite, 562
- Porcupine and Kirkland gold districts,
Ontario, 274
- Porosity of rocks, 72, 406, 407, 408
- Porphyry coppers, 76
- Portland cement, 479, 622
- Portugal, arsenic, 310
copper, 185
pyrite, 543
radium, 333

Portugal, titanium, 137

Potash, 561

domestic deposits, 562

foreign deposits, 562

mode of occurrence, 561

origin, 62, 562

selected readings, 563

use, 563

Potassium, 21, 67

Potonie, H., 392

Potosi, Bolivia, silver district, 278

Potstone, 629

Potters' sand, 511

Pottery clay, 471

Pozzuolian cement, 483

Prase, 624

Pressure in oil and gas wells, 423

Primary mineral deposits, 31, 33

Primary openings in rocks, 60

Prince William Sound, Alaska, copper district, 183

Principles of the formation of mineral deposits, 15-82

Productivity of oil wells and fields, 429-435

Products of weathering, 63

Propane, 388, 389

Proustite, 240

Prussian blue, 526

Psilomelane, 125

Pulpstones, 595

Pumice, 596, 622

Pumicite, 596

Pumpelly, Raphael, 95

Pyrargyrite, 240

Pyrite, 541

alteration, 73

domestic deposits, 542

foreign deposits, 543

mode of occurrence, 26, 33, 44, 48, 50,
52, 76, 150, 250, 252, 260, 318,
345, 501, 542, 575

origin, 542

physical properties, 541

selected readings, 544

uses, 543

Pyrolusite, 125

Pyrophyllite, 622, 623

Pyroxene, 26, 46, 48

Pyrrhotite, 26, 33, 44, 48, 179, 183, 248,
257, 279, 324

Q

Quartz, 623

composition, 623

mode of occurrence, 26, 44, 46, 48, 50,
52, 64, 74, 149, 201, 250, 252, 255,
257, 269, 274, 318, 492, 500, 606,
623

physical properties, 623

use, 7, 507, 527, 623, 627

varieties, 624

Quartzite, defined, 500

origin, 78, 500

uses, 7, 79, 512, 595

Quebec, chromite, 120

chrysotile, 533

copper, 185

ilmenite, 34

magnesite, 586

mica, 619

molybdenite, 131

phlogopite, 619

zinc, 228

Queensland, arsenic, 310

cobalt, 123

gold, 277

lead, 225

molybdenum, 131

sapphire, 610

tin, 293

zinc, 225

Quicksilver, 317

Quirke, G. T., 95

R

Radium (*see* Uranium and radium).

Raleigh, Sir Walter, 384

Rand gold district, Transvaal, South Africa, 270

Rare earths, 26, 591

Rare elements, economically important in crust, 24

in igneous rocks, 23

Rastall, R. H., 43, 273

Ray, Ariz., copper district, 176

Realgar, 309

Reeside, J. B., 517

Reeves, Frank, 349

Refractories, 120, 301, 334, 586, 589, 625

Refractory clay, 470

Regional metamorphism, 78

- Regionally metamorphosed deposits, 78,
79, 104
- Replacement deposits, 157, 205
- Replacement vein, definition of, 37
- Reservoir rock, 406, 409
- Reservoirs for oil and gas, 409-418
- Residual clays, 469
- Residual iron ores, 108, 110
- Residual ore deposits, 31, 64, 73, 204, 579
- Residual products of weathering, 64, 72,
73
- Retort clay, 470
- Retort oven, 377
- Rhode Island, granite, 493
graphite, 614
- Rhodesia, chromite, 34, 118
coal, 372
copper, 185
vanadanium, 143
- Rhodium, 134, 323
- Rhodochrosite, 52, 125, 269, 276
- Rhodonite, 125, 269, 276
- Rhyolite, 492
- Rich, M. N., 143
- Rico, Colo., zinc-lead district, 221
- Ries, H., 553
- Rio Tinto, Spain, pyrite, 543
- Rock, definition of, 15
- Rock crystal, 8, 624
- Rock salt, 547
- Rocky Mountain coal field, 363
- Rocky Mountain oil and gas field, 444
- Roll, 356
- Roofing sand, 506
- Roscoelite, 142
- Rose quartz, 624
- Rottenstone, 596, 622
- Ruby, 610, 611, 613
- Ruby silver, 278
- Rumania, oil, 447
- Russell, W. L., 401
- Russia, chromite, 120
coal, 371
garnet, 610
gold, 279
iron, 110
lapis lazuli, 610
manganese, 127
mercury, 321
oil, 447
platinum, 34, 324
topaz, 610
- Russia, tourmaline, 610
- Russian Turkestan, radium, 332
- Ruthenium, 134, 323
- Rutilated quartz, 624
- Rutile, 26, 137
- Rutland, Vt., marble quarries, 497
- S
- St. John del Rey, Brazil, gold mine, 278
- St. Peter sandstone, 509
- Sales, R. H., 161
- Salisbury, R. D., 355
- Salt, 544
analyses, 545
domestic deposits, 546
geologic distribution, 546
mode of occurrence, 547
origin, 69, 551-554
physical properties, 545
production, 555
salt domes, 549
selected readings, 555
use, 554
- Salt Creek oil and gas field, Wyo.,
444
- Salt domes, 413, 549
- Saltpeter, 565
- San Juan gold-silver district, Colo.,
268
- Sand and gravel, 504
composition, 504
kinds, 505
mode of occurrence, 504
selected readings, 513
treatment, 505
use, 505, 622
- Sandberger, F., 70
- Sandstone, 500
domestic deposits, 501
physical properties, 500
use, 8, 501
- Sandstone as a reservoir rock, 406
- Santa Fe Springs oil pool, Calif., 443
- Santa Rita, N. M., 175
- Sapphire, 46, 610, 611, 612, 613, 624
- Sarawak, British Borneo, oil, 451
- Sard, 624
- Sardonyx, 624
- Satin spar, 515
- Satin white, 622
- Saxony, uraninite, 332

- Scheelite, 138
 Schist, 78
 Schoolcraft, H. R., 197
 Scotland, siderite, 110
 Scythestones, 596
 Secondarily enriched ore deposits, 31, 75, 149, 201
 Secondary mineral deposits, 31, 58, 73
 Secondary openings in rocks, 60
 Secondary sulfide enrichment, 74, 76, 149
 Sedimentary iron deposits, 68, 107, 110
 Sedimentary rocks, 31, 32, 585, 603
 Selenite, 515
 Selenium, 327
 production, 328
 selected readings, 328
 use, 327
 Semianthracite, 340, 344, 363
 Semibituminous coal, 340, 344
 Seminole oil pool, Okla., 440
 Semiprecious stones (*see* Gems and semi-precious stones).
 Senegal, Africa, titanium, 137
 Sepiolite, 628
 deposits, 629
 mode of occurrence, 628
 selected readings, 629
 uses, 629
 Sericitization, 52
 Serpentine, 499
 domestic deposits, 500
 physical properties, 499
 use, 500, 622
 Sewer-pipe clay, 470
 Shafter, Tex., silver district, 266
 Shale, 408, 526, 622
 Shallow vein zone deposits, examples, 55
 metals, 52
 minerals, 52
 mode of occurrence, 55
 origin, 55
 shape, 53
 size, 53
 texture, 53
 Shan States, tungsten, 138
 Shansi province, China, anthracite, 371
 Shasta County, Calif., copper district, 178
 Shearer, H. K., 299
 Siam, spinel, 610
 tin, 291
 zircon, 610
 Siberia, coal, 371
 gold, 279
 lapis lazuli, 610
 platinum, 324
 Sicily, sulfur deposits, 538
 Siderite, 50, 88, 94, 110, 149, 201, 270, 575
 Siegenite, 123
 Sienna, 527
 Signal Hill oil pool, Calif., 443
 Silesia, cadmium, 314
 lead, 228
 zinc, 228
 Silica, deposition in sea water, 68, 622
 Silica brick, 627
 Siliceous sinter, 624
 Silicification, 52
 Silicomanganese, 116, 144
 Silicon, 21, 187
 Silicon carbide, 597, 627
 Silicospiegeleisen, 116, 128
 Silimanite, 627
 Silver, 12, 50, 52, 150, 260, 276, 277 (*see also* Gold and silver).
 Sinai Peninsula, copper mines, 9, 10
 Slate, 501
 composition, 501
 domestic deposits, 502
 origin, 78, 501
 physical properties, 501
 use, 7, 503, 526
 Slate flour, 503, 622
 Slickensides, 356
 Sluiceway, 243
 Smackover oil pool, Ark., 440
 Smaltite, 123
 Smith, George O., 366
 Smithsonite, 75, 199, 212, 219, 223
 Smoky quartz, 8, 624
 Soapstone, 7, 622, 629 (*see also* Tale).
 Sodium, 21
 Sodium bicarbonate, 568
 Sodium carbonate, 568
 Sodium compounds (*see* Natural sodium compounds).
 Sodium cyanide, 563
 Sodium nitrate, 564
 Sodium sulfate, 569
 Solder, 230, 294, 308, 315

- Soluble products of weathering, carried downward, 70, 72
 removed by surface waters, 66
- South Africa, amosite, 532
 cadmium, 313
 chromite, 120
 coal, 372
 crocidolite, 532
 diamonds, 34, 612
 gold, 270
 platinum, 325
 radium, 332
 tin, 291
- South Australia, cadmium, 314
- South Carolina, barite, 581
 china clay, 471
 columbite, 329
 corundum, 34, 597
 mica, 621
 monazite, 592
 phosphate rock, 559
 pyrophyllite, 623
 tin, 291
- South Dakota, abrasives, 595
 bentonite, 600
 coal, 363
 feldspar, 606
 gold, 247
 gypsum, 516
 limonite, 108
 manganese, 127
 mica, 619
 spodumene, 590
 tantalum, 329
 tin, 291
 tungsten, 139
- Southeastern Missouri, cadmium, 314
 lead district, 206
- Southwest Africa, cadmium, 313
 diamonds, 612
 vanadium, 143
- Southwestern coal field, 363
- Southwestern Wisconsin zinc-lead district, 222
- Spain, bismuth, 311
 copper, 185
 hematite, 110
 lead, 228
 mercury, 321
 potash, 562
 pyrite, 543
 sepiolite, 629
- Spain, zinc, 228
- Spathic iron ore, 89
- Specularite, 44, 48, 87, 597
- Spencer, A. C., 257
- Sperrylite, 323
- Sphalerite, 44, 48, 50, 52, 150, 199, 211, 216, 219, 220, 221, 222, 223, 269, 345, 575
- Spiegeleisen, 116, 128
- Spilker, A., 394
- Spindletop oil field, Tex., 429, 446
- Spinel, 33, 46, 48, 610, 611, 628
- Split, 355
- Spodumene, 590
- Spore coal, 348
- Spurr, J. E., 43, 268
- Stable minerals, 59
- Standard sand, 512
- Stannite, 290, 291
- Star-quartz, 624
- Stassfurt, Germany, salt and potash deposits, 552, 561, 562
- Steatite, 629
- Steel, defined, 91
- Steel-molding sand, 506
- Stellite, 121, 124
- Stibnite, 52, 306, 307, 318
- Stone, R. W., 517, 553
- Stone, 486
 history, 13, 486
 kinds, 492
 physical properties, 488
 selected readings, 503
- Stone ages, 6
- Stone-ware clay, 471
- Storer, F. H., 392, 394
- Strontianite, 591
- Strontium, mode of occurrence, 591
 ore minerals, 591
 selected readings, 591
 use, 591
- Structural materials, 465-535
- Stuart, Murray, 397
- Subbituminous coal, 341, 344, 363, 371
- Sublimed white lead, 524, 622
- Sudbury, Ont., cobalt, 123
 iridium, 325
 nickel, 34, 132, 133, 134
 osmium, 325
 palladium, 325
 platinum, 325
 ruthenium, 325

Sulfide enrichment, 75, 149
 Sulfur, 537
 domestic deposits, 538
 foreign deposits, 538
 mode of occurrence, 35, 537
 origin, 537
 physical properties, 537
 selected readings, 544
 uses, 540, 566, 622
 Sulfur dioxide, 34
 Sulfuric acid, as a solvent, 72, 540
 Sullivan lead-zinc mine, B. C., 225
 Super-phosphates, 560
 Surface deposits, 56
 Sweden, magnetite, 34, 110
 pyrite, 543
 Syenite, 492
 Sylvanite, 330
 Sylvite, 562
 Syncline, 412
 Syngenetic ore deposits, defined, 31
 description, 33
 localities where found, 34

T

Talc, 629
 domestic deposits, 630
 mode of occurrence, 630
 origin, 630
 physical properties, 629
 production, 632
 selected readings, 632
 uses, 527, 622, 631
 Talckene, 622
 Tanganyika, diamonds, 612
 Tantalite, 329
 Tantalum, domestic deposits, 329
 foreign deposits, 329
 mode of occurrence, 329
 ore minerals, 329
 origin, 329
 production, 330
 selected readings, 330
 uses, 329
 Tar, 380
 Tarr, W. A., 67, 68, 215, 393, 399, 490
 Tasmania, cadmium, 314
 coal, 372
 copper, 186
 lead, 225
 Tasmania, osmiridium, 325
 tin, 293
 zinc, 225
 Taylor, McKenzie E., 347
 Tellurium, ore minerals, 330
 selected readings, 331
 uses, 330
 Tennantite, 50, 160
 Tennessee, ball clay, 471
 barite, 581
 bauxite, 301, 626
 bentonite, 600
 coal, 362
 copper, 179
 fluorite, 573
 hematite, 99
 lime, 521
 limonite, 108
 marble, 497
 oil and gas, 439
 phosphate rock, 558
 pottery clay, 471
 slate, 503
 tripoli, 633
 zinc, 224
 Terne plate, 294
 Terra alba, 622
 Terra cotta clay, 470
 Tetrahedrite, 50, 181, 221, 264, 265, 269, 270
 Texas, anhydrite, 516
 asphalt, 528
 bentonite, 600
 coal, 363, 364
 columbite, 329
 feldspar, 606
 fullers' earth, 608
 granite, 493
 graphite, 614
 gypsum, 517
 mercury, 320
 mica, 619
 oil and gas, 440, 446
 potash, 562
 salt, 549
 silver, 266
 strontium, 591
 sulfur, 538
 tin, 291
 Thenardite, 569
 Theories of origin of mineral deposits
 contrasted, 70, 77

- Thetford Mines, Que., chrysotile deposits, 533
- Thiessen, R., 394
- Thomas, C. R., 402
- Thomson, Ellis, 95
- Thorium (*see* Monazite and thorium, 591).
- Tiger-eye, 624
- Tin, domestic deposits, 290
 foreign deposits, 291
 gangue minerals, 290
 mode of occurrence, 27, 44, 48, 64, 290
 ore minerals, 290
 origin, 290
 physical properties, 289
 production, 295
 selected readings, 296
 use, 293
- Tin plate, 294
- Tintic, Utah, arsenic, 310
 bismuth, 311
 copper district, 181
 lead district, 210
 silver district, 261
- Titaniferous magnetite, 107
- Titanite, 26, 137
- Titanium, deposits, 136
 mode of occurrence, 136
 ore minerals, 136
 origin, 136
 production, 137
 selected readings, 137
 uses, 137
- Titanium white, 525
- Titanox, 526
- Tolman, C. F., 394, 396, 443
- Toluol, 381
- Tonapah, Nev., gold-silver district, 267
- Topaz, 46, 48, 290, 293, 610, 611
- Torbernite, 331
- Tourmaline, 46, 48, 290, 293, 606, 610, 611, 612
- Transported clays, 470
- Transvaal, Union of South Africa,
 amosite, 532
 gold, 270
 mica, 619
- Trap rock, 492
- Trask, P. D., 399
- Travertine, 494
- Tremolite, 44
- Trinidad, asphalt, 528
 oil, 450
- Tripoli, 632
 deposits, 633
 mode of occurrence, 633
 origin, 633
 physical properties, 633
 production, 634
 selected readings, 634
 use, 596, 622, 634
- Tri-State area, cadmium, 314
 zinc district, 211
- Trona, 569
- Tuff, 492
- Tungsten, domestic deposits, 138
 foreign deposits, 139
 mode of occurrence, 27, 35, 44, 48, 50, 138
 ore minerals, 138
 origin, 138
 production, 141
 selected readings, 141
 uses, 139
- Tunisia, iron, 110
 lead, 228
 zinc, 228
- Turkey, chromium, 120
 emery, 597
- Turquoise, 8, 610, 611, 612
- Type metal, 308
- U
- Ulexite, 567
- Umber, 527, 622
- Union of South Africa, amosite, 532
 crocidolite, 532
 diamonds, 612
- Upper Mississippi Valley zinc-lead district (*see* Southwestern Wisconsin zinc-lead district).
- Ural Mountains, garnet, 610
 platinum, 34, 324
 tourmaline, 610
- Uraninite, 331, 332
- Uranium and radium, domestic deposits, 332
 foreign deposits, 332
 mode of occurrence, 331
 ore minerals, 331
 origin, 331

- Uranium and radium, physical properties
 of minerals, 331
 production, 333
 selected readings, 333
 use of radium, 333
 use of uranium, 332
 Uses (given under each material).
 Usiglio, J., 553
 Utah, antimony, 307
 arsenic, 310
 barite, 581
 bentonite, 600
 bismuth, 311
 cadmium, 314
 carnotite, 332
 coal, 363
 copper, 167, 181
 diatomaceous earth, 604
 fluorite, 573
 gold, 240, 282
 gypsum, 516
 lead, 210
 limonite, 108
 magnetite, 105
 oil and gas, 444
 onyx marble, 500
 phosphate rock, 559
 potash, 562
 salt, 551
 silver, 261
 sodium sulfate, 569
 strontium, 591
 sulfur, 540
 tungsten, 139
 vanadium, 142
 zinc, 216
 Utah Copper Company, 153, 169, 240
- V
- Vadose water, 61, 62, 74
 Van Hise, C. R., 71, 95, 97
 Vanadinite, 142
 Vanadium, domestic deposits, 142
 foreign deposits, 143
 mode of occurrence, 142
 ore minerals, 142
 origin, 142
 production, 143
 uses, 143
 Vein, defined, 36
 origin, 36
 special features, 37
 Venetian red, 526
 Venezuela, asphalt, 528
 magnesite, 586
 oil, 452
 Verde antique, 499
 Vermiculite, 527
 Vermilion iron range, Minn., 93
 Vermilion red, 321, 526
 Vermont, abrasives, 596
 china clay, 471
 chrysotile, 533
 granite, 493
 marble, 497
 serpentine, 500
 slate, 502
 talc, 631
 Vesuvianite, 44
 Victoria, Australia, gold, 277
 Virginia, abrasives, 597
 anhydrite, 516
 arsenic, 310
 barite, 581
 bentonite, 600
 coal, 362
 columbite, 329
 diatomaceous earth, 604
 feldspar, 606
 ground sand, 512
 gypsum, 516
 lime, 521
 limonite, 108
 manganese, 127
 mica, 621
 pyrite, 542
 salt, 546
 sandstone, 501
 slate, 502
 talc, 631
 titanium, 137
 Vitrain, 342
 Vogt, J. H. L., 324
 Vug, 38
- W
- Warren, C. M., 392, 394
 Washburne, C. W., 434
 Washington, H. S., 19, 20, 21, 22, 23, 24,
 25, 87, 147, 238, 289, 297, 306, 309,
 323
 Washington, abrasives, 597
 antimony, 307

- Washington, basalt, 493
 chromite, 117
 chrysotile, 533
 coal, 364
 diatomaceous earth, 604
 dumortierite, 627
 fluorite, 573
 magnesite, 586
 mercury, 321
 molybdenum, 131
 monazite, 592
 sandstone, 501
 serpentine, 500
 sodium carbonate, 569
 strontium, 591
 Washington County, Mo., barite, 580
 Water associated with oil, 428
 Water level, 61
 Water table, 61
 Water vapor, 26, 34
 Watson, T. L., 543
 Weathering, 58
 Weed, W. D., 160
 West Australia, gold, 277
 tantalum, 329
 West Texas oil pool, 440
 West Virginia, calcium and magnesium
 chloride and bromine, 576
 coal, 362
 engine sand, 511
 glass sand, 509
 ground sand, 512
 lime, 521
 oil and gas, 439
 salt, 550
 strontium, 591
 Westerly, R. I., granite quarries, 493
 Western Interior coal field, 363
 Whetstones, 596
 White, David, 348, 349, 355
 White, I. C., 411, 431
 White lead, 229, 524, 622
 Whiting, 527, 622
 Whitney, J. D., 95, 146
 Wiechert, E., 19
 Willemite, 200, 215
 Williamson, E. D., 19
 Wilson, W. B., 402
 Winchell, N. H., 95
 Wisconsin, barite, 581
 feldspar, 606
 Wisconsin, granite, 493
 ground sand, 512
 hematite, 93
 lead, 222
 lime, 521
 mica, 619
 sandstone, 501
 zinc, 222
 Witwatersrand (*see* Rand).
 Wöhler, F., 297
 Wolframite, 48, 138, 290, 293
 Wollastonite, 44
 Woody coal, 348
 Wrought iron, 91
 Wulfenite, 130
 Wurtzilite, 528
 Wyoming, bentonite, 599
 chromite, 117
 chrysotile, 533
 coal, 363
 gypsum, 516
 hematite, 102
 oil and gas, 444
 phosphate rock, 559
 platinum, 324
 salt, 546
 sodium carbonate, 569
 sodium sulfate, 569
 sulfur, 540
 titaniferous magnetite, 107

X

 Xanthochroite, 313
 Xyloid, 340, 342, 347

Y

 Yunnan, China, tin, 291

Z

 Zacatecas silver district, Mexico, 276
 Zinc, 27, 44, 48, 50, 52 (*see also* Lead and zinc).
 Zinc dust, 232
 Zinc oxide, 232, 524, 622
 Zinc pigments, 232, 524
 Zincite, 200, 215
 Zircon, 26, 334, 610, 611, 628

Zirconium, domestic deposits, 334
foreign deposits, 334
mode of occurrence, 26, 334
ore minerals, 334
origin, 334
production, 335

Zirconium, selected readings, 335
uses, 334, 628
Zirconium-ferrosilicon, 116
Zonal theory of mineral deposition, 42,
159, 208, 293
Zone of chemical weathering, 60



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